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DE-ICING OF AN AIRCRAFT-ENGINE INDUCTION SYSTEM

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

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By Henry A. Essex

SUMMARY

A program of tests on engine induction system de-icing by means of de-icing fluids and by heated air has been conducted in a special laboratory at the National Bureau of Standards. The induction system tested consisted of a simulated air scoop, a Holley 1375-F carburetor, a carburetor adapter, and a Wright R-1820, G-200 supercharger rear section. The de-icing fluid injection devices used included the standard Holley alcohol vent ring (Holley part No. 2383), a modified Holley vent ring (Holley part No. 3089), a set of four standard Army nozzles (part Nos. AN4023 and AN4024), and a set of modified Army nozzles which were similar to the standard nozzles except for larger exit orifices. The de-icing fluids tested were Solox D-I, isopropyl alcohol, anhydrous ethyl alcohol, S.D.30, and Shellacol. In most of the tests refrigeration icing was produced by maintaining the carburetor-air temperature at 40° F while spraying free water into the air stream at a rate of 250 grams per minute.

It was found in the fluid de-icing tests made with the original Holley alcohol vent ring that it was necessary to inject de-icing fluid into the carburetor at a rate of at least 60 pounds per hour in order to attain rapid recovery of air flow and fuel-air ratio. This Holley ring, because of its poor fluid distribution, was found to be an unsatisfactory de-icing fluid injection device at lower fluid-flow rates. However, at fluid-flow rates of 60 pounds per hour and above, rapid recovery was obtained.

In some of the tests distribution of de-icing fluid over the surfaces of the carburetor was poor, and ice formed again after recovery of initial air flow in spite of continued injection of the de-icing fluid. This phenomenon, referred to as re-icing, occurred in the de-icing tests made with the original Holley ring at fluid-flow rates below 50 pounds per hour. In a series of ice-prevention tests using Solox D-I, a minimum fluid flow rate of 50 pounds per hour was required to prevent ice from forming in the carburetor and adapter.

The modified Holley ring, the orifices of which are fewer in number and smaller in diameter than those of the original type, and also the Army alcohol nozzles, were found to have much better distribution characteristics at low flow rates than the original Holley ring and, as a result, apparently eliminated the occurrence of re-icing.

The time necessary to restore operable fuel-air ratio (0.065) from the extremely lean ratios accompanying refrigeration icing was usually $1\frac{1}{2}$ to $2\frac{1}{2}$ times that necessary to restore cruising air flow when either of the Holley vent rings was used as a fluid injection device with Solex D-I.

When used with isopropyl alcohol, the standard Army nozzles were superior in de-icing effectiveness to other fluid combinations at de-icing fluid flow rates of 30 to 40 pounds per hour, initial air flow being restored more rapidly and operable fuel-air ratio being restored in periods no longer than those attained with the other fluid systems. At higher rates of injection the Army nozzles were about eqial to other systems.

Results of several of the tests indicated that, to make the most effective use of a de-icing fluid, it should be injected into the induction system just upstream of and as close as possible to the ice formation to be removed. For removal of ice from the adapter it was found that the de-icing fluid spray should cover evenly and completely all exposed surfaces of the carburetor. The results indicated that to comply with these requirements supplementary fluid injection systems should be provided for de-icing of other parts of an induction system where ice might be expected to accumulate.

Manipulation of the throttle during the first few seconds of fluid de-icing was found to hasten recovery to initial air flow rate but did not appear to have a noticeable effect on recovery of operable fuel-air ratio.

It was found that the amount of fluid necessary to remove ice from the induction system was a function of the rate of air flow to be recovered and some inverse function of carburetor air temperature. The amount of fluid required was substantially independent of the rate of fluid injection at flow rates ranging from 30 to 80 pounds per hour for any given method of injection, although re-icing occured at some of the lower flow rates.

Results of several tests made to investigate the removal of impact ice formed at a carburetor-air temperature of 25° F indicated that saturated carburetor air at a temperature of 85° F was slightly superior to Solox D-I fluid sprayed into the air stream through the modified Holley vent ring at 80 pounds per hour. The data also indicated that isopropyl alcohol injected just ahead of the carburetor through the standard Army nozzles at a flow rate of 42 pounds per hour was almost as effective a de-icing agent as either of the other two systems. When the original Holley vent ring was used with Solox D-I, it was not possible to attain adequate removal of impact ice at de-icing fluid-flow rates of either 60 or 80 pounds per hour.

Isopropyl alcohol proved superior to Solox D-I in displaying less tendency toward re-icing and greater effectiveness in the prevention of ice formations. It appeared from the results of this program that desirable characteristics of an effective de-icing fluid should include low vapor pressure, low latent heat of vaporization, and a large fusion temperature depression.

All of the de-icing fluids except Solox D-I had a slight corrosive effect on aluminum alloy. The S.D.30 fluid, which contained no inhibitor, also exhibited a corrosive effect on brass and copper.

It was not possible to draw quantitative conclusions from the results of the heat de-icing tests because of unforeseen difficulties experienced in controlling the temperature and humidity of the intake air, and because the laboratory apparatus failed to simulate adequately an aircraft installation. The data indicated, however, that a reasonable amount of heat added to the carburetor air stream can be as effective in the restoration of air flow and operable fuel-air ratio as any of the fluid de-icing combinations that were tested. Heated air in the presence of free water was effective as a de-icing agent when sufficient heat was supplied to vaporize the water and raise the temperature of the moist air above limits of icing (80° F for this induction system).

INTRODUCTION

The object of the tests described in this report was to investigate the effectiveness of fluid and heat de-icing equipment currently used with engine induction systems and also to determine optimum values for de-icing fluid flow rates and heat input to attain rapid recovery of engine power after an appreciable percentage of power has been lost as a result of ice formation. A range of engine-operating conditions and various simulated weather conditions were covered in order that the results of this work would find broad application.

These tests represent a portion of a research program on induction-system icing conducted at the National Bureau of Standards under NACA sponsorship. An investigation of the icing characteristics of the engine induction system used in the present program has been made. The results of this work are described in reference 1. This research project is being financed jointly by the Army, the Navy, and the National Advisory Committee for Aeronautics. Support also has been received from the Civil Aeronautics Administration.

EQUIPMENT

The engine induction system used for the tests described in this report consisted of a 90° pipe bend simulating an air scoop, Holley 1375-F carburetor, a carburetor adapter, and a Wright R-1820, G-200 supercharger rear section. The tests were conducted in an altitude laboratory at the National Bureau of Standards. The various parts of this laboratory induction system test installation and also the method of operating this apparatus to produce ice formations in the induction system are described in detail in reference 1. The fuel used in the tests was a white unleaded gasoline of 73 octane rating with distillation characteristics similar to those of currently used aviation fuels. The induction system test apparatus and details of the induction system pertinent to the present tests are shown in figures 1 to 3.

For the present program this apparatus is unchanged except for the provision of Army alcohol-injection nozzles, de-icing fluid pressure tank, and a slight rearrangement of the apparatus necessary for introducing heated air into the induction system.

Several alcohol-injection devices were tested in the program, including a standard Holley vent ring (part No.A2383), modified Holley ring (part No. A3089), a set of four standard Army nozzles (AN4023 and AN4024), and a set of four slightly modified Army nozzles. The standard Holley ring is an aluminum-alloy casting which has the same inner dimensions as the interior walls of the carburetor and is installed just above the throttle body.

De-icing fluid enters this hollow rectangular ring through one passage and is injected into the air stream through 16 orifices of 0.031-inch diameter, four orifices being located on each side of the ring. The modified Holley vent ring is similar in general dimensions to the standard type, but has eight orifices 0.016 inch in diameter, which are drilled into the ring so that the fluid is ejected from them at an upward angle of 40°, four of the orifices being located on each of two opposite sides of the ring. The alcohol spray is directed across the carburetor normal to the axis of the throttles.

The set of four Army nozzles, which have orifices of 0.020-inch diameter, was installed in the walls of the air-intake duct 2 inches above the carburetor, with two of the nozzles located on each of two opposite sides. The modified Army nozzles, which were used in several of the tests, are similar to the standard nozzles except that they have 0.0225-inch-diameter orifices. The nozzle location 2 inches above the carburetor, which was used throughout most of the tests on the Army nozzles, represents a typical service installation. During one series of tests a set of standard Army nozzles was mounted in the elbow of the air scoop, as shown in figures 1 to 3, in order to determine the relative efficiency of the nozzles for another service installation.

For forcing the de-icing fluid into the carburetor through the Holley ring, a standard electrically driven de-icing fluid pump was employed, rate of flow being controlled by a rheostat and a bypass valve. In the tests made with the Army nozzles, it was necessary to force de-icing fluid into the induction system under higher pressure than that required with the Holley ring. For this purpose a sealed tank containing the de-icing fluid was employed. The de-icing fluid was supplied under a pressure which could be varied between 5 and 100 pounds per square inch by means of air pressure supplied through an adjustable pressure regulator valve. Rate of flow through the standard Army nozzles was controlled by fluid pressure.

The de-icing fluids tested included Solox D-I, isopropyl alcohol, anhydrous ethyl alcohol, S.D.30, and Shellacol. Solox D-I consists of a mixture of 90 percent ethyl and 10 percent methyl alcohol to which is added a corrosion inhibitor and one gallon of gasoline per 100 gallons of mixture. The isopropyl alcohol used is a liquid of 98 percent commercial purity. S.D.30 is a mixture of 90 percent ethyl and 10 percent methyl alcohol which contains no corrosion inhibitor or further denaturing material. The physical properties of S.D.30 are similar to those of Solox D-I. The specific gravity of each of the above fluids is 0.789 at a temperature of 20° C. Shellacol consists of ethyl alcohol denatured with methyl alcohol, ethyl acetate, methyl isobutyl, ketone, and aviation gasoline. The specific gravity of this product is 0.80 to 0.82 at a temperature of 15° C.

Rate of flow of de-icing fluid into the induction system was measured by a rotameter. Because of the different flow characteristics of the fluids tested it was found necessary to calibrate the rotameter for each fluid in order to insure accurate measurements.

For the heat de-icing tests, the intake air was heated by passing it through six banks of steam coils, as shown in figure 1. Rate of flow of heated air was controlled by a thermostatically operated butterfly valve which bled heated air from the alternate air source into the main air duct to be mixed with the cold air. With this equipment it was found possible to raise the temperature of the air to 150° F at an air-flow rate of 5000 pounds per hour if no free water were present. The temperature of the intake air was measured by a pressure-bulb thermometer installed in the intake duct near the mouth of the air scoop, and to this thermometer was connected a thermostat which, in turn, regulated the operation of the butterfly hot-air valve. A special window, shown in figure 1, was built into the air-scoop elbow in order to permit observation of the formation of ice and its removal.

A twelve-point recording potentiometer with a range of 0° to 400° F was employed to measure the temperature of the intake air, the air temperature at the steam heating coils, and the engine-compartment temperature during the heat de-icing tests. Eight elements of this instrument were connected to the carburetor air temperature thermocouple, and in this way the air temperature was measured every 4 seconds.

The carburetor used in this research program was not equipped with a means of complete compensation for changes in the fuel-air mixture due to changes in altitude or in air temperature. The latter factor was considered important in connection with this program in view of the heat de-icing tests that are included. Several tests were made therefore to determine the change in initial fuel-air ratio resulting from increases in carburetor air temperature. This calibration curve is shown in figure 4.

TEST PROCEDURE

In most of the de-icing tests the carburetor-air temperature was set at 40° F, and the ice which formed in the induction system was the refrigeration or fuel-evaporation type. A typical ice formation of this type is shown in figure 5. Several tests were also made at 25° F carburetor-air temperature to investigate removal of impact ice by means of de-icing fluid and by application of heat. An impact ice formation is seen in figure 6. The effect of ice forming in the system on the air-flow rate and the mixture ratio under these two conditions before the de-icing process was started is shown in figure 7. The Holley vent ring was chosen as the standard for comparing the effectiveness of the various de-icing fluid injection devices.

The method of forming refrigeration ice in the induction system was in all cases similar to that employed during the program of icing tests made on this induction system described in reference 1. The initial rate of air flow in most of the tests was set at 4000 pounds per hour, the mixture ratio at 0.070, and the carburetor-air temperature of 40° F. After these conditions had been established in each test, free water was introduced into the air stream at a rate of 250 grams per minute. When sufficient ice had formed as a result of these conditions to reduce the air flow rate to 2000 pounds per hour, which is 50 percent of the initial rate, the de-icing process, employing either a de-icing fluid or heated air, was started. In most of these tests the fuel-air ratio fell below the minimum operable value, which was considered to be 0.065. The test was then continued until all ice was observed to be removed from the induction system, until the air flow had stabilized, or until definite evidence of re-icing was displayed.

Re-icing can be described as the formation of ice in the carburetor after initial recovery of air flow, the ice forming in spite of the continued injection of de-icing fluid. Re-icing was manifested by a drop in air flow and by enrichment of the mixture.

Visual observations of all important variables, including rate of air flow, fuel flow, and air temperature, were made at intervals of 6 seconds during the first 2 minutes of the de-icing period in each test. The interval between measurements was then lengthened to 12 seconds for the next minute and, after this critical portion of the de-icing process, the data were recorded at longer intervals.

During most of the tests the water spray was continued throughout the de-icing period. This procedure represents the situation in which flight through icing conditions is continued while alcohol or heated air is being applied to remove the ice formation. Tests were also made in which the water spray was turned off at the beginning of the de-icing period in order to simulate the conditions of de-icing without further rain ingestion into the induction system.

The free water ingestion rate of 250 grams per minute was held constant during the test and is equivalent to a rain density of 10 grams per cubic meter within the air scoop at cruising power at sea-level pressure and 40° F carburetor-air temperature. Rate of water ingestion into an induction system in flight is primarily a function of airplane speed, dimensions of the air scoop, and outside rain density. The latter may be only a fraction of the rain density within the air scoop, owing to the ramming effect. The total amount of water ingested also may be affected by the application of carburetor heat, since heat increases the capacity of air to carry water as vapor. Details of the operating conditions and also of the results obtained during each test are contained in table I.

DISCUSSION OF TESTS AND RESULTS

The results of the de-icing tests described in this report are presented in table I and in the accompanying charts. As shown in the table, the test program was divided for conveniece into various series of tests, A to N, according to the various specified conditions. The alcohol de-icing tests are included in series A to L. The other two series are the heat de-icing tests.

Although it is believed that the results of this investigation will be of general value, it is necessary to point out that the data contained in the report should be applied with some caution, especially in connection with the operation of induction systems other than the type tested in this program. Both icing and de-icing are influenced to a certain extent by the design and flow characteristics of different engine induction systems.

Ice formations are also not always identical in nature for similar icing conditions in the same induction system. This can be seen by comparing the results given in the report of tests made at substantially identical conditions. Another factor to be considered in applying the results of this investigation is that the icing which occurred in these tests was much more severe than would be normally expected in flight at the temperatures investigated. An experienced pilot would be expected to become aware of the ice formation and to take protective measures before the engine power is reduced by 50 percent, the level reached in the laboratory tests. Because of this latter factor, the results contained in this report are believed to be somewhat conservative.

No tests were made to investigate the effect of icing on mixture distribution to the individual engine cylinders; however, experience has shown that obstructions in the air passage causing flow diversions affect distribution.

In most of the fluid de-icing tests Solox D-I, injected into the carburetor through the original-type Holley alcohol vent ring, was employed. This combination was therefore chosen as a standard for comparing the effectiveness of other fluid injection devices and fluids.

Fluid De-Icing Tests

Recovery of emergency power - Holley ring.- It was the object of the first group of tests (Series A) to determine the time required to attain the air-flow rate corresponding to emergency engine power (7000 lb/hr) by the injection of de-icing fluid at various rates of flow through a Holley vent ring after sufficient ice had formed in the induction system to reduce the air flow to 2000 pounds per hour. The initial rate of air flow was set at 4000 pounds per hour, as in almost all of the tests of the program. At the beginning of the de-icing period in each test of this series the throttle was opened wide. The mixture setting was left unchanged when the throttle was opened, although in flight the mixture ratio would have been increased by 0.015.

The results of the tests of series A are shown in figures 8 and 9. It was found that 90 percent (6300 lb/hr) of the air-flow rate necessary for emergency power could be restored in 1¼ minutes with de-icing fluid sprayed into the carburetor at a rate of 60 pounds per hour and in 1 minute for a de-icing fluid rate of 90 pounds per hour. The time required to recover a fuel-air ratio of 0.080 was about equivalent to that for recovery of 90 percent air-flow rate.

Recovery of cruising power - Holley ring. - The tests of series B were made to determine the time necessary to recover cruising rate of air flow (4000 lb/hr), by the injection of Solox D-I and isopropyl alcohol through the Holley vent ring after 50 percent of the initial air-flow rate had been lost because of the formation of ice. In this group of tests the usual procedure of continuing the water spray during the de-icing as well as the icing period of the tests was followed. The throttle was held fixed at the initial cruising setting throughout the tests.

The results of these tests are shown in figures 10 to 12. It was found that with Solox D-I 90 percent of the initial cruising air flow rate was restored in a period of 33 seconds at a de-icing fluid flow rate of 60 pounds per hour and in 15 seconds at a de-icing fluid flow rate of 80 pounds per hour. The time required to recover minimum operable fuel-air ratio (0.065) was almost twice that required for 90 percent recovery of initial air flow in these tests. The rates of air-flow recovery attained with the injection of isopropyl alcohol at rates of 40 pounds per hour and above were equivalent to those attained with Solox D-I at equal flow rates. Isopropyl alcohol was inferior to Solox D-I, however, in recovery of operable fuel-air ratio at all fluid-flow rates.

It was found in the tests of series B that re-icing occurred during the injection of de-icing fluid at flow rates up to 50 pounds per hour. In the case of Solox D-I the re-icing was sufficiently severe to reduce the air-flow rate to 3300 pounds per hour and to enrich the mixture ratio to 0.094 at a de-icing fluid flow rate of 40 pounds per hour. This re-icing occurred after the cruising air-flow rate, 4000 pounds per hour, had been restored. As shown in figure 10, only a very slight amount of re-icing occurred in the isopropyl tests of this series at fluid-flow rates above 20 pounds per hour.

The enrichment of the mixture during re-icing was caused by the formation of ice on the throttles and in the venturi throat. This resulted from the throttling action of the ice in the venturi which reduced the air flow but maintained high air velocities and therefore low pressures in the vicinity of the fuel nozzles. Since the fuel-flow rate was controlled by the difference between a metered fuel pressure and the venturi suction, the fuel-flow rate was therefore maintained or increased by re-icing.

It was determined by visual observations made through the window in the air-scoop elbow that the re-icing phenomenon was caused to a large extent by the nonuniform spray of de-icing fluid made by the Holley vent ring. Very little de-icing fluid was observed to flow through the orifices located at the corner of the Holley ring farthest from the de-icing fluid intake line to the vent ring, especially at low rates of de-icing fluid flow. Below this starved corner of the Holley ring ice formed in the carburetor venturis and in some cases above the throttles. These ice formations were accelerated by the reduction of carburetor-air temperature caused by the evaporation of de-icing fluid.

The superiority of isopropyl alcohol in preventing the occurrence of re-icing was attributed to the differences between the physical properties of isopropyl and Solox D-I. Isopropyl alcohol has a lower vapor pressure and, as a result, a smaller percentage of this fluid evaporates during the de-icing process than occurs with Solox D-I. Because its latent heat of vaporization is also less than that of the ethyl or methyl alcohol, the same amount of isopropyl in evaporating has a lesser refrigerating effect.

De-Icing without Water Ingestion - Holley Ring

During the next group of tests (series C), in contrast to most of the tests of this program, the water spray was turned off at the start of the de-icing period in order to represent the situation of changing over to an alternate air intake by means of which water ingestion could be eliminated during the de-icing. Otherwise the test conditions of this series were similar to those of the preceding series. Solox D-I was used as the de-icing fluid.

In the tests involving de-icing fluid flow rates above 40 pounds per hour, the difference in time for recovery of air-flow rate and fuel-air ratio between the dry and the wet air conditions was negligible. It was also noted that there was no tendency toward re-icing in these tests. This would be expected since the cause of the icing was substantially eliminated when the water was turned off. The results of these tests are shown in figures 13 and 14.

Because with an alternate air-intake system a moderate increase in carburetor-air temperature can be expected, two tests were included in this series in which the air temperature was set at 50° F and at 70° F, respectively, rather than at the usual value of 40° F. It was found, however, that the amount of heat added to the intake air by these temperature rises was insufficient to cause an appreciable reduction in the time required for recovery of the initial rate of air flow.

<u>Standard Army alcohol nozzles - cruising power.</u> - Several de-icing tests (series D) were made with the standard and the modified types of Army alcohol nozzles, using Solox D-I, in icing conditions similar to those of series B. In each of these tests the alcohol-injection nozzles were installed in their usual location in the walls of the air-intake duct 2 inches above the carburetor.

The results of these tests (figs. 15 and 16) showed that with both types of nozzles the time required for 90 percent recovery of initial cruising air flow was somewhat longer than that required with the Holley ring for equal rates of de-icing fluid flow. The time required for recovery of operable fuel-air ratio varied from about $2\frac{1}{2}$ times the period for 90-percent air-flow recovery at a de-icing fluid injection rate of 60 pounds per hour to about three times the air-flow-recovery period at a 30-pounds-per-hour injection rate. Very little difference could be detected between the relative de-icing effectiveness of the two types of Army nozzles using Solox D-I. No tendency of re-icing was observed in any of the tests of this group. This was attributed to the excellent de-icing fluid spray patterns produced with the Army nozzles. The spray completely covered the carburetor surfaces at all rates of fluid flow tested.

From figure 16 it can be seen that at de-icing fluid flow rates above 30 pounds per hour no appreciable decrease in time of air-flow-rate recovery was produced. Increased fluid-injection rates required higher fluid pressures which produced greater atomization and penetration of the sprays. These factors probably improved fluid distribution, but this was more than offset by the accelerated fluid evaporation also resulting from increased atomization and penetration. When a less volatile fluid such as isopropyl alcohol was used, this effect was not apparent.

Flow of de-icing fluid through the standard Army nozzles is controlled by fluid pressure. It was noted in general in the tests of this program made on the standard Army nozzles that at the de-icing fluid pressures generally used in airplane installations, 10 to 20 pounds per square inch, that the rates of recovery of air flow attained were very little different. Tests with the modified Army nozzles, which are similar to the standard type except for slightly larger orifices, were included in this program in order to investigate the higher rates of alcohol flow for a comparison with the two types of Holley vent rings. It should be noted that alcohol pressures above 20 pounds per square inch are not usually available in aircraft fluid de-icing installations.

In the tests of series E the de-icing effectiveness of the standard- and the modified-type Army nozzles with isopropyl alcohol in restoring cruising power was investigated. The results are shown in figures 17 to 20.

It was found that the modified Army nozzles with isopropyl alcohol were about equal in recovery of cruising air-flow rate to the Holley alcohol vent ring with Solox D-I but were considerably inferior in fuel-air-ratio recovery. The data indicated that the standard Army nozzles were equally as effective a de-icing agent as the Holley vent ring with Solox D-I in recovery of both cruising air flow and operable fuel-air ratio at de-icing fluid injection rates of 40 pounds per hour or more. At flow rates lower than this, or in the range in which the Army nozzles are usually operated, they were somewhat superior to other fluid systems tested in air-flow recovery, 90 percent of cruising air flow rate being restored in 36 seconds at a de-icing fluid flow rate of 30 pounds per hour.

Several tests were made to determine the effectiveness of the standard Army alcohol nozzles when installed in the elbow of the air scoop, as shown in figures 1 to 3. It was found that ice was removed from the induction system at a much slower rate than when the Army nozzles were installed at their usual location, as shown in the contrast in the slopes of the air-flow curves in figures 16 and 19. This difference in effectiveness is somewhat more evident in figure 20.

It was observed that the poor performance of the Army nozzles when installed in the air-scoop elbow was the result of nonuniform distribution of the de-icing fluid at the carburetor. A part of the de-icing fluid was carried by its own inertia to the rear side of the air-scoop elbow while another portion flowed along the bottom of the air scoop. Thus only a small percentage of the de-icing fluid passed through the center of the carburetor, and that portion flowing along the scoop walls was considerably diluted. During one test made with the standard Army nozzles at the alternate location in the air-scoop elbow, the water spray was turned off at the start of the de-icing period.

Stopping ingestion of water in the air stream had little immediate effect on the air-flow recovery since the water remaining on the walls of the scoop and the duct continued to be swept through the carburetor. When most of this residual water had been ingested, the de-icing fluid became more effective. This was evidenced by the sudden rise in air flow in run 37A after a period of $2\frac{1}{2}$ minutes.

<u>Modified Holley ring - cruising power</u>. - Because of the poor de-icing fluid spray distributions at low fluid-flow rates obtained with the standard Holley ring, resulting in re-icing, the modified Holley alcohol vent ring was procured and tested. These tests, series F, were made under the usual conditions of series B, with Solox D-I used as the de-icing fluid.

The results, shown in figures 21 and 22, indicated very little difference in de-icing effectiveness, as measured by rate of recovery of cruising air flow and operable fuel-air ratio, between the two types of Holley vent rings. With the modified Holley ring, however, a much more uniform spray of de-icing fluid was obtained, covering the various surfaces of the carburetor with fluid at all rates of flow. As a result of this good spray pattern, re-icing was apparently eliminated.

Effect of throttle opening on de-icing. - The object of the next group of tests (series G) was to investigate the effectiveness of fluid de-icing at various throttle openings which produced ice-free air flow rates from 500* to 7000 pounds per hour, representing a range from idling up to emergency engine power. The standard Holley alcohol vent ring with Solox 4.I was employed. In each test the mixture ratio was set at a value which would produce satisfactory engine operation at the corresponding air-flow rate. The de-icing fluid was injected into the air stream at two rates of flow, 40 and 60 pounds per hour, for each of the four throttle openings.

The results of this group of tests, (fig. 23) showed that with de-icing fluid injected into the carburetor at 60 pounds per hour the time required to attain 90-percent recovery of the initial rate of air flow was equal (about 18 sec) at air-flow rates of 500, 2000, and 4000 pounds per hour. The recovery time was somewhat longer at each rate of air flow for the tests in which de-icing fluid was injected at 40 pounds per hour. In the two full-throttle tests, however, the time required to restore 90 percent of the initial air flow rate was considerably longer - 1.3 and 1.1 minutes for de-icing fluid flow rates of 40 and 60 pounds per hour, respectively. This difference resulted from the fact that more ice must be removed from the adaptor at full throttle to provide the passage area necessary for the higher flow rates. In the two tests started

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*In the tests performed at 500 and 2000 lb/hr initial air flow rates, the carburetor manufacturer's propeller-load curve was used for an air-flow calibration. This was done by setting the throttle angle and carburetor pressure drop to give the desired air flow value as determined from the curve. As the icing proceeded, the carburetor pressure drops were recorded and referred to the curve to find the corresponding air flows. The fact that the increase in throttle drop was due to ice formation rather than to throttle closing was a source of error; however, it was assumed that the readings made in this manner were within the accuracy of the test data.

at 500-pounds-per-hour air-flow rate, engine-idling conditions, the mixture was very rich at the start of the de-icing but became less rich as the de-icing proceeded. The mixture ratio remained richer than the initial value even after it could be seen that most of the ice had been removed. This condition was the result of ice forming in the venturis, affecting the flow of fuel.

Effect of throttle manipulation. - Several exploratory tests were included in the program (series H) to investigate the effect of various throttle manipulations on the de-icing effectiveness of Solox D-I sprayed into the carburetor through the standard Holley vent ring. These tests were made under the icing conditions of series B. The rate of de-icing fluid flow was set at 60 pounds per hour for each test.

The result of one of those tests (run 50, fig. 24) showed that the technique of repeatedly closing and opening the throttle to cruising setting at a rate of about 1 cycle per second for the first 10 seconds after the start of the de-icing period produced 90-percent recovery of the cruising air flow rate in a period of 6 seconds, a more rapid recovery rate than achieved in any other fluid de-icing test in this program. The data also indicated that the air flow can be restored more quickly by opening the throttle wide at the start of the fluid de-icing period than by opening it in several steps. The rapid recovery of initial air-flow rate achieved by manipulation of the throttle appeared to be due to the loosening of the ice by the pressure surges of the air. It was observed that ice did not form directly on the throttle during any of these tests. Recovery of operable fuel-air ratio did not appear to be improved by throttle manipulation.

The beneficial effect of throttle manipulation can also be seen in the results of the tests of series A (figs. 8 and 9) in which the throttle was opened wide at the start of the de-icing period of each test. In analyzing these data it was found desirable to plot curves in figure 9 to show recovery of air flow and fuel-air ratio for cruising and also for full power. These data indicated that recovery of both cruising air flow and operable fuel-air ratio was accomplished more rapidly by opening the throttle than by leaving it fixed as in series B.

It must be pointed out that the data obtained thus far on the effect of throttle manipulation were insufficient for a thorough analysis. A more complete investigation of the effect of throttle manipulation on alcohol de-icing effectiveness appears desirable.

Comparison of de-icing fluids. - Several tests were made to determine the relative effectiveness of various de-icing fluids when injected into the carburetor by the standard Army nozzles (series I). The tests were made under the usual icing conditions of series B. De-icing fluids tested included ethyl alcohol, Shellacol, and S.D.30.

Because a total of only five tests were conducted in this series, including a single test with Shellacol and two with each of the other fluids, it was not possible to make definite conclusions from the results. The data indicated tentatively that air-flow-recovery rates obtained with ethyl alcohol and with S.D.30 were roughly in the same range as those obtained with Solox D-I and isopropyl alcohol injected through the Army nozzles. Recovery of operable fuel-air ratio with these fluids was slower, however. On the basis of one test, Shellacol appeared slightly superior in de-icing effectiveness to the other fluids.

De-icing with vaporized alcohol. - Two tests (series J) were made to investigate the effectiveness of vaporized isopropyl alcohol as a de-icing agent. One of these tests was made under the usual icing conditions of series B, while in the second test the water spray was turned off at the start of the de-icing period. The alcohol was heated to a temperature of about 110° F and then sprayed into the air-intake duct at a point a short distance downstream from the hot air supply duct.

The results of these two tests (fig. 26) showed that vaporized alcohol is a far less effective de-icing agent than liquid alcohol, a time period of 2 minutes being required to restore 90 percent of the cruising air flow rate in both cases. A quantity of 0.98 pound of vaporized isopropyl alcohol was required to produce 90-percent air-flow recovery with injection of free water continuing through the test and 1.20 pounds to produce the same recovery when the water was shut off. This can be contrasted with average values of 0.36 pound and 0.41 pound of liquid isopropyl alcohol required to produce 90-percent air-flow recovery under the same conditions. The rate of flow of vaporized alcohol was directly proportional to the rate of air flow. Thus, in figure 26 it can be seen that the rate of alcohol flow in one test ranged from 20 pounds per hour at the start of the de-icing period to 40 pounds per hour at the end. In the other test the alcohol-flow rate was somewhat higher.

The evaporation of the de-icing fluid tended to reduce the carburetor-air temperature, but because the alcohol was introduced into the intake duct upstream from the pressure-bulb thermometer which thermostatically regulated the flow of heated air into the intake duct, heat was added to the air to maintain the set temperature. This heat input assisted somewhat in the removal of the ice formations, making the performance of the alcohol vapor appear somewhat better than otherwise would have been possible.

Anti-icing effectiveness of de-icing fluids. - The tests of series K were performed to determine the effectiveness of isopropyl alcohol and Solox D-I in preventing the formation of ice. The de-icing fluids were injected into the carburetor through the standard Holley vent ring at various rates of flow and were turned on with the water spray at the beginning of each test. The tests were made at cruising air-flow rate of 4000 pounds per hour and at the usual 40° F carburetor-air temperature.

It was found in the results of these tests (fig. 27) that, with Solox D-I, a de-icing fluid flow rate of at least 50 to 60 pounds per hour was required in order to prevent the formation of ice. Isopropyl alcohol proved superior as an anti-icing agent, an alcohol-flow rate of 30 pounds per hour holding the air flow almost constantly to its initial rate. The greater effectiveness of isopropyl was attributed to its lower vapor pressure and latent heat of vaporization, which were pointed out as the causes for its superiority over Solox D-I in preventing the occurrence of re-icing at low rates of de-icing fluid flow in the de-icing tests. The ice formations which occurred during the anti-icing tests were similar to the formations referred to as re-icing. Enrichment of the mixture, characteristic of all runs during which ice formed, was caused by ice forming in the venturi throat.

<u>Removal of impact icing.</u> - Removal of impact-ice formations from the induction system by the introduction of de-icing fluids into the carburetor through various injection devices was investigated in several tests under series L. The usual procedure of forming ice was followed, except that the carburetor-air temperature was held at 25° F instead of at 40° F. The impact ice which resulted formed over the throttle and bridged across the carburetor venturis.

The results of these tests, shown in figure 28, indicated that, with Solox D-I injected into the carburetor at a flow rate of 80 pounds per hour, the modified Holley ring, owing to its better distribution characteristics, was considerably superior to the standard Holley ring in removing impact ice. The initial air-flow rate and operable fuel-air ratio were not recovered under these conditions with the standard Holley ring. This was attributed to poor distribution of de-icing fluid which appeared especially critical under impact-icing conditions.

In one test of this group, heated air (temp. raised from 25° to 85° F) was substituted for alcohol as the de-icing agent. The result was a slightly more rapid removal of the impact-ice formation than with de-icing fluid injected at a rate of 80 pounds per hour through the modified Holley vent ring, 90 percent of the initial cruising flow rate being restored in a period of 48 seconds. It was found in one test made with Army nozzles using isopropyl alcohol injected at a flow rate of 40 pounds per hour (20 lb/sq in. press.) that the impact-ice formation was removed almost as rapidly as with an 80-pound-per-hour flow rate of Solox D-I injected into the carburetor through the modified Holley vent ring.

It is planned to conduct additional tests on the removal of impact ice from induction sytems in order to investigate de-icing at lower carburetor-air temperatures and to reproduce the formation of snow in the induction systems. In these tests it is expected that a wider range of variables will be investigated than was possible in the present brief series.

<u>Amount of fluid required for de-icing.</u> - In analyzing the results of the de-icing tests, table II and several charts (figs. 29 to 32) were prepared to determine the amount of fluid required to restore the initial rate of air flow

under various test conditions. These data showed that the amount of fluid required is a function of the rate of air flow that must be restored. On the basis of two impact-icing tests made at 25° carburetor air temperature (runs 67 and 70) in which almost complete recovery of air-flow rate and fuel-air ratio were attained, it appears that the recovery time is some inverse function of the carburetor-air temperature. It was found that the amount of de-icing fluid required was substantially independent of the rate of injection for any given method at de-icing fluid flow rates of 30 to 80 pounds per hour, although re-icing may occur at the lower flows.

In order to restore 90 percent of the cruising air-flow rate under the usual test conditions with water continuing to flow through the induction system during the de-icing process, an average of about one-half pound of alcohol was required. It appears desirable to conduct additional tests to determine more thoroughly the amount of alcohol required to restore initial power at various air temperatures and air-flow rates. The method and rate of de-icing fluid injection appears to be of importance in recovery of fuel-air ratio. In the majority of the tests (series B to F) recovery of operable fuel-air ratio required 1½ to 2½ times that required for air-flow recovery.

<u>Corrosive effect of de-icing fluids</u>. - As a result of the clogging of the small orifices of the standard Army nozzles by deposits observed during some of the de-icing tests, a brief laboratory study was made to determine the possible corrosive effect of various de-icing fluids on certain metals. In these tests strips of polished brass, copper, and 17S-T aluminum alloy were suspended in the de-icing fluids which were contained in test tubes. The various test specimens remained partially immersed in the fluids for a period of about 3 weeks. None of the fluids except S.D.30 was found to have any corrosive effects on either copper or brass. This fluid, which does not contain a corrosion inhibitor, caused blackening of the copper specimen and iridescence of the brass specimen after a period of 2 or 3 days' immersion. All of the fluids except Solox D-I had a slight corrosive effect on aluminum alloy in the presence of copper.

Heat De-Icing Tests

Two groups of tests (series M and N) were made to investigate the use of heated air for the removal of refrigeration ice from the induction system. The icing conditions of these tests were similar to those of most of the alcohol de-icing tests, with the throttle held fixed at the cruising air flow rate and the carburetor-air temperature set at 40° F. In the first group of tests the water spray was turned off at the start of the de-icing period, while in the second group of tests the water spray was left on throughout the tests. The results of the tests are shown in figures 33 and 34.

Study of the data indicated that quantitative conclusions from the results of those tests were not warranted because of unforeseen difficulties experienced in controlling the temperature and humidity of the carburetor air. The test setup also failed to simulate adequately an actual aircraft installation.

In interpreting these data it should be noted that the heated air temperatures varied considerably from the initial values during the period when the major portion of the de-icing was occurring. These temperature variations were attributed to the inherent lag of the apparatus and instruments, and also to the large proportion of the heat which was used in evaporating water present in the air rather than in raising the air temperature. An indication of the temperature loss due to water evaporation may be seen in figure 35, a record taken during one of the tests of carburetor air temperature and the temperature in a dry portion of the intake duct upstream from the point of water injection.

During some of the heat de-icing tests made at the higher ranges of temperature, 95° to 140° F, the fuel-air ratio became slightly enriched. This enrichment resulted from the fact that in being heated the density of the air was decreased and full recovery of mass air flow was prevented because the carburetor was only partially compensated for temperature changes.

The tests demonstrated the fact that heated air carrying sufficient heat as temperature rise, or temperature rise plus additional humidity, can be fully as effective in restoring fuel-air ratio and air flow as any of the de-icing fluid systems tested. When free water was allowed to flow into the induction system during the heated-air de-icing tests, the available temperature rise was much lower. It was found, however, that effective de-icing was accomplished in spite of the free water present and the limited temperature rise, provided enough heat was supplied to raise the carburetor-air temperature above the limits of icing (80° F) for the induction system. (See curve of limiting icing conditions, reference 1.)

CONCLUSIONS

Because of the differences in icing characteristics of various types of engine induction systems, the following conclusions are considered directly applicable only to the induction system tested and for the temperatures of these tests. Much of the data contained in this report, however, are expected to be of general value.

1. A de-icing fluid flow rate of at least 60 pounds per hour of either Solox D-I or isopropyl alcohol injected into the carburetor by either the standard or the modified Holley alcohol vent ring was required to attain rapid recovery of cruising air flow after the air flow was reduced by 50 percent because of the formation of ice in the induction system. The time to recover operable fuel-air ratio (0.065 at cruising air flow) was in general $1\frac{1}{2}$ to $2\frac{1}{2}$ times that necessary for the restoration of 90-percent initial air-flow rate. Recovery of fuel-air ratio was somewhat longer with isopropyl alcohol.

2. The results indicated that no improvement in de-icing effectiveness was gained by stopping the ingestion of free water into the induction system at the start of the de-icing process, but the possibility of re-icing was apparently eliminated.

3. It was observed that an effective de-icing fluid injection device should distribute the fluid in the induction system so that all parts of the region where ice has formed, including the throttle and other carburetor surfaces, are completely washed by the fluid in order to eliminate the ice and to prevent re-icing.

4. De-icing fluid should be injected as closely upstream as possible to the region to be de-iced in order to reduce

fluid evaporation and dilution by water on the walls of the induction system and in the air stream. To comply with this requirement, supplementary systems may be needed for parts of the induction system other than the carburetor.

5. It was concluded from a few exploratory tests that manipulation of the carburetor throttles during the first few seconds of fluid de-icing apparently resulted in more rapid elimination of large ice formations from the induction system than would be possible with the throttle held fixed.

6. The amount of de-icing fluid required to restore initial air flow and operable fuel-air ratio increased with increase in the rate of air flow that must be recovered and was probably some inverse function of carburetor-air temperature. For a given method of fluid injection the amount of de-icing fluid required to attain recovery of the air flow was substantially independent of the rate of de-icing fluid flow in the flow range of 30 to 80 pounds per hour.

7. The standard Holley alcohol vent ring, because of poor de-icing fluid distribution at injection rates of less than 50 pounds per hour of Solox D-I, permitted considerable re-icing. Re-icing was noticeably reduced by substituting isopropyl alcohol for Solox D-I. The use of the modified Holley vent ring or the standard Army nozzles, injection devices which have better distribution characteristics, apparently eliminated re-icing.

8. In order to prevent the formation of serious refrigeration ice with free water flowing through the carburetor at a rate of 250 grams per minute, it was necessary to inject Solox D-I at a rate of 50 pounds per hour or isopropyl alcohol at a rate of 30 pounds per hour into the induction system. These data indicated the superiority of isopropyl alcohol over Solox D-I as an anti-icing agent. The elimination of re-icing by the use of the modified Holley ring and the standard Army nozzles indicated that these devices would have better anti-icing quality than the standard Holley ring.

9. When used with isopropyl alcohol, the standard Army nozzles were superior in de-icing effectiveness to other fluid combinations at de-icing fluid flow rates of 30 to 40 pounds per hour, initial air flow being restored more rapidly and operable fuel-air ratio being restored in periods no longer

than those attained with the other fluid systems. At higher fluid flow rates the standard Army nozzles with isopropyl alcohol were equal in de-icing effectiveness to other fluid systems.

10. It was found that a de-icing fluid, to be most effective, should have a low vapor pressure, a low latent heat of vaporization, and a large freezing point depression. Isopropyl alcohol proved superior to Solox D-I in reducing the occurrence of re-icing and was a better anti-icing agent because of its superiority in the first two qualities.

11. It was tentatively determined that S.D.30 and ethyl alcohol were roughly equivalent to Solox D-I and isopropyl alcohol in air flow recovery but were inferior in restoring operable fuel-air ratio. On the basis of a single test, Shellacol appeared slightly superior to the other fluids.

12. All of the de-icing fluids tested except Solox D-I showed a slight corrosive effect on aluminum alloy. The S.D.30 fluid, which does not contain a corrosion inhibitor, also had a slight corrosive effect on brass and copper.

13. Because of unforeseen difficulties experienced with the equipment, it was not possible to draw quantitative conclusions from the heat de-icing tests. The data indicated, however, that heated air properly applied was fully as effective in restoring air flow and operable fuel-air ratio as any of the fluid de-icing systems tested.

14. It was found that heated air in the presence of free water provided effective restoration of air flow and operable fuel-air ratio if enough heat was imparted to the saturated air to raise the temperature above the temperature limit of icing for the induction system (80° F).

National Bureau of Standards,
Washington, D. C.

REFERENCE

1. Kimball, Leo B.: Icing Tests of Aircraft-Engine Induction Systems. NACA ARR, Jan. 1943.

TABLE II.– AMOUNT OF ALCOHOL REQUIRED TO RESTORE 90 PERCENT OF INITIAL AIR FLOW UNDER VARIOUS TEST CONDITIONS

Series	Alcohol injection device[1]	Air temp. (0° F)	De-icing fluid	Recovered air flow (lb/hr)	Water injection rate (cc/min)	Av. amount of alcohol used (lb)
A	H.R.	40	Solox D-I	6300	250	1.3
B	H.R.	40	Solox D-I	3600	250	.50
	H.R.	40	Isopropyl	3600	250	.55
C	H.R.	40	Solox D-I	3600	0	.44
D	M.A.N.	40	Solox D-I	3600	250	1.2
	A.N.	40	Solox D-I	3600	250	.53
E	A.N.E.	40	Isopropyl	3600	250	4.8
	M.A.N.	40	Isopropyl	3600	250	.59
	A.N.	40	Isopropyl	3600	250	.39
F	M.H.R.	40	Solox D-I	3600	250	.52
G	H.R.	40	Solox D-I	450	250	.40
	H.R.	40	Solox D-I	1800	250	.25
	H.R.	40	Solox D-I	3600	250	.41
	H.R.	40	Solox D-I	6300	250	.99
I	A.N.	40	Ethyl	3600	250	.60
	A.N.	40	S.D.30	3600	250	.49
L	A.N.	25	Isopropyl	3600	250	1.26
	M.H.R.	25	Solox D-I	3600	250	1.33

[1]H.R., standard Holley vent ring; M.A.N., modified Army nozzles; A.N., standard Army nozzles; A.N.E., Army nozzles at scoop elbow; M.H.R., modified Holley vent ring.

TABLE I.- DE-ICING OF AN AIRCRAFT ENGINE INDUCTION SYSTEM BY MEANS OF DE-ICING FLUID AND BY HEATED AIR
HOLLEY CARBURETOR 1375-F WRIGHT 1820-G-200 INTERMEDIATE REAR SECTION

Icing						De-icing																	
Run number	Carb. air temp.(deg F)	Initial air flow (lb/hr	Initial F/A	Free water injection(ml/min)	Icing time (min)	Air flow at start (lb/hr)	F/A at start (1)	Carb. air temp. (deg F)	Free water injection(ml/min)	De-icing fluid	Injecting apparatus (2)	Rate of fluid inject.(lb/hr)	Fluid pressure (lb/sq in.)	Throttle manipulation (3)	Length of de-icing period(min)	Recovery time 90 percent air flow (min)	Time to recover to 0.065 F/A(min)	Amount of fluid for 90 percent recovery (lb)	F/A at 90% air flow recovery	Max. air flow recovery(lb/hr)	F/A at max. air flow recovery	Time for max air flow recovery (min)	Remarks
Series A	(See figures 8,9))																						
1	40	4000	.070	250	12.5	2000	.038	40	250	Solox D-I	H.R.	10	-	2	20	10.75	8	1.79	.068	6950	.061	20	Slow fluctuating recovery; lean mixture.
2	40	4000	.070	250	14.0	2000	.045	40	250	Solox D-I	H.R.	20	-	2	20	6.0	2.2	2	.069	6500	.077	20	Slow recovery never reaching full emergency power.
3	40	4000	.070	250	14.25	2000	.047	40	250	Solox D-I	H.R.	30	-	2	13	1.5	1.5	.75	.080	7150	.068	1.5	Slow mixture recovery.
4	40	4000	.070	250	14.3	2000	.043	40	250	Solox D-I	H.R.	40	-	2	13	.5	.7	.33	-	7150	-	.5	Ice formation came out in one chunk.
5	40	4050	.069	250	15.5	2000	.048	40	250	Solox D-I	H.R.	50	-	2	16	1.9	1.1	1.5	.065	6840	.082	6.0	Moderate recovery.
6	40	4000	.070	250	18.5	2000	.042	40	250	Solox D-I	H.R.	60	-	2	14	.4	-	.4	-	7040	.082	13	Very rapid recovery.
7	40	4000	.070	250	17.3	2000	.041	40	250	Solox D-I	H.R.	70	-	2	13	1.2	.4	1.4	.075	7060	.080	3	Rapid recovery.
8	40	4000	.070	250	17.75	2000	.037	40	250	Solox D-I	H.R.	80	-	2	18	1.2	.5	1.6	.084	7140	.085	10	Rapid recovery.
9	40	4050	.069	250	15.0	2000	.037	40	250	Solox D-I	H.R.	90	-	2	16	1.0	.6	1.5	.079	7150	.092	10	Rapid recovery.
11	40	4000	.071	250	15	2000	.045	40	250	-	-	0	-	2	8	-	-	-	-	-	-	-	Continued icing until flow dropped to zero.
4-A	40	4000	.070	250	15	2000	.040	40	250	Solox D-I	H.R.	40	-	2	20	3.2	1.6	2.2	.087	7600	.078	17.45	Large chunk of ice remaining on nozzle delayed recovery.
Series B	(See figures 10,11,12)																						
12	40	4050	.071	250	16.5	2000	.033	40	250	Solox D-I	H.R.	10	-	1	23	14.5	17	2.33	.039	3800	.067	17	Very slow recovery of air flow and mixture.
13	40	3940	.072	250	15.5	1980	.038	40	250	Solox D-I	H.R.	20	-	1	21	1.6	.3	.50	.056	3940	.067	3.0	Re-icing down to 2600 lb/hr flow. Ice in venturi.
14	40	3980	.070	250	16.75	1960	L	40	250	Solox D-I	H.R.	30	-	1	20	1.0	1.08	.50	.060	3900	.068	1.5	Re-icing to 3000 lb/hr. Venturi ice.
15	40	3980	.073	250	15.5	1960	.049	40	250	Solox D-I	H.R.	40	-	1	22	.75	1.35	.50	.059	3980	.070	1.66	Re-icing to 3290 lb/hr. Air flow.
16	40	3940	.071	250	16.0	1960	L	40	250	Solox D-I	H.R.	50	-	1	20	.58	1.0	.49	.056	3940	.071	2.5	Slight re-icing.
17	40	3940	.071	250	20.5	1960	L	40	250	Solox D-I	H.R.	60	-	1	14	.58	.83	.58	.058	3900	.069	2.0	No visible ice remained in induction system.
18	40	4020	.070	250	18.0	1960	.056	40	250	Solox D-I	H R.	80	-	1	12	.25	.83	.33	.048	3940	.069	1.42	No visible ice remaining in induction system.
13-A	40	3950	.070	250	24	2000	.041	40	250	Isopropyl	H.R.	20	-	1	22	4.2	8.8	1.4	.056	3850	.062	4.5	Slow recovery, re-icing to 3300 lb/hr air flow.
14-A	40	4000	.067	250	21.5	2000	.048	40	250	Isopropyl	H.R.	30	-	1	22	2.0	7	1.0	.054	3950	.065	14	Slow recovery, slight re-icing.
15-A	40	4000	.070	250	19.0	2000	L	40	250	Isopropyl	H.R.	40	-	1	13	.7	5.2	.47	.045	3950	.063	2.2	Slight re-icing.
16-A	40	4000	.070	250	14.5	2000	L	40	250	Isopropyl	H.R.	50	-	1	11	.5	.53	.42	.064	3970	.070	1.8	Rapid recovery, slight re-icing.
17-A	40	4000	.072	250	14.0	2000	L	40	250	Isopropyl	H.R.	60	-	1	7	.3	1.4	.3	.055	3920	.071	4.0	Rapid recovery, ice remaining on nozzle bar.
Series C	(See figures 13,14))																						
19	40	4000	.069	250	33	2000	.038	40	0	-	-	0	-	1	4	-	-	-	-	-	-	-	Flow dropped off to zero.
20	40	4000	.069	250	18.5	1800	L	40	0	Solox D-I	H.R.	20	-	1	20	.7	14	.47	.054	3900	.064	10	Large chunk remaining in adapter.
21	40	4000	.070	250	31	2000	.037	40	0	Solox D-I	H.R.	30	-	1	14	.9	2.2	.45	.052	3950	.068	3.5	Moderate but complete recovery.
22	40	4050	.069	250	14.5	2000	L	40	0	Solox D-I	H.R.	40	-	1	10	.8	1.6	.53	.051	4000	.068	2.4	Large diminishing chunk left in adapter.
23	40	4050	.069	250	15.5	2000	L	40	0	Solox D-I	H.R.	60	-	1	5	.5	1.4	.5	.055	4000	.069	2.6	Adapter cleared completely of ice.
24	40	4050	.070	250	15.5	2000	L	40	0	Solox D-I	H.R.	50	-	1	5	.4	1.2	.33	.032	4000	.071	3.5	Adapter cleared of ice.
25	40	4000	.070	250	13.5	2000	.040	40	0	Solox D-I	H.R.	70	-	1	4	.4	.6	.47	.062	4000	.070	1.4	Adapter cleared of ice.
26	40	4030	.072	250	19	2000	L	50	0	Solox D-I	H.R.	60	-	1	7	.4	.7	.4	.056	4080	.071	4.0	Complete recovery.
27	40	4100	.071	250	21.3	2000	L	70	0	Solox D-I	H.R.	60	-	1	5	.4	.8	.4	.057	4080	.072	2.2	Complete recovery.
Series D	(See figures 15,16)																						
28	40	4000	.065	250	31	2000	.035	40	250	Solox D-I	M.A.N.	20	-	1	23	6.0	-	2.0	.057	3850	.064	15	Slow recovery.
29	40	4000	.070	250	16.5	2000	.038	40	250	Solox D-I	M.A.N.	40	-	1	18	.9	4.0	.6	.054	3980	.070	12	Moderate recovery.
30	40	4000	.070	250	22.75	2000	L	40	250	Solox D-I	M.A.N.	60	-	1	15	1.0	2.4	1.0	.056	3950	.070	4	Moderate recovery.
31	40	4000	.071	250	20.25	2000	.040	40	250	Solox D-I	A.N.	29	10	1	16	.9	1.7	.43	.054	4030	.069	14	Moderate recovery, ice completely gone.
32	40	4000	.068	250	20.25	2000	.051	40	250	Solox D-I	A.N.	37	20	1	16	1.0	7.0	.62	.052	3990	.067	14	Ice completely removed.
Series E	(See figures 17,18,19,20)																						
33	40	4000	.070	250	29.5	2000	L	40	250	Isopropyl	M.A.N.	20	-	1	20	1.7	-	.57	.054	3880	.061	14	Slow incomplete recovery.
34	40	4000	.069	250	23.3	2000	.038	40	250	Isopropyl	M.A.N.	40	-	1	16	.9	10	.6	.054	3940	.065	12	Moderate recovery, ice left in adapter.
35	40	4000	.070	250	23.3	2000	.038	40	250	Isopropyl	M.A.N.	60	-	1	16	.6	2.0	.6	.059	3930	.069	7	Moderate recovery, ice left in adapter.
36	40	4000	.071	250	18.3	2000	L	40	250	Isopropyl	A.N.E.	27	10	1	22	18	-	6.6	.053	3700	.057	20	Slow incomplete recovery.
37	40	4020	.070	250	17.6	2000	L	40	250	Isopropyl	A.N.E.	36	20	1	20	3.8	11	2.98	.054	3970	.071	18	Slow recovery. Ice left in adapter.
37-A	40	4030	.070	250	38.5	2000	L	40	0	Isopropyl	A.N.E.	44	20	1	15	2.8	4.5	2.05	.055	4000	.065	14	Slow recovery. Ice gone after 15 min.
38	40	4000	.069	250	19.5	2000	.052	40	250	Isopropyl	A.N.	30	10	1	10	.6	.5	.3	.066	3900	.071	5	Rapid recovery. Ice left in adapter.
38-A	40	4000	.070	250	29.5	2000	.038	40	250	Isopropyl	A.N.	31.5	10	1	22	.3	11.0	.16	-	3980	.064	9	Rapid recovery. Ice in adapter.
39	40	4020	.070	250	15.0	2000	L	40	250	Isopropyl	A.N.	40.5	20	1	10	.5	.93	.34	.061	3980	.071	5	Rapid recovery. Ice left in adapter.
39-A	40	4000	.069	250	22.5	2000	.043	40	250	Isopropyl	A.N.	43	20	1	10	1.1	2.3	.79	.057	3950	.067	2.4	Slow recovery.
39-A'	40	4000	.071	250	28	2000	.036	40	250	Isopropyl	A.N.	40.5	20	1	20	.5	1.5	.34	.063	3950	.069	8	Rapid recover. Ice in adapter.
40	40	4000	.070	250	16.5	2000	L	40	250	Isopropyl	A.N.	62	40	1	10	.4	.6	.41	.049	3900	.070	2.8	Rapid recovery. Ice left in adapter.
41	40	4000	.070	250	11.5	2000	L	40	0	Isopropyl	A.N.	40.5	20	1	7	.6	.9	.41	.057	3950	.070	1	Rapid recovery. Ice left in adapter.
Series F	(See figures 21,22)																						
42	40	4000	.070	250	20	2000	L	40	250	Solox D-I	M.H.R.	30	-	1	10	1.4	1.9	.7	.058	3950	.071	5	Moderate recovery. No re-icing.
43	40	4000	.070	250	15	2000	L	40	250	Solox D-I	M.H.R.	80	12	1	7	.2	.4	.26	.050	3950	.067	.8	Very rapid recovery.
44	40	4000	.070	250	18.75	2000	L	40	250	Solox D-I	M.H.R.	60	8	1	10	.6	.8	.6	.056	3950	.068	1.0	Rapid recovery. No re-icing.

[1]L, mixture lean beyond operating range; R, mixture rich beyond operating range.

[2]H.R., Holley ring; A.N., standard Army Air Forces nozzles; M.A.N., modified Army Air Forces nozzles; A.N.E. standard Army Air Forces nozzles at scoop elbow; M.H.R., modified Holley ring; W.S.N., medium water spray nozzle.

TABLE I.- (concluded)

Icing						De-icing																	
Run number	Carb. air temp. (deg F)	Initial air flow (lb/hr)	Initial F/A	Free water injection (ml/min)	Icing time (min)	Air flow at start (lb/hr)	F/A at start (1)	Carb. air temp. (deg F)	Free water injection (ml/min)	De-icing fluid	Injecting apparatus (2)	Rate of fluid injection (lb/hr)	Fluid pressure (lb/sq in.)	Throttle manipulation (3)	Length of de-icing period (min)	Recovery time 90% air flow (min)	Time to recover to 0.065 F/A (min)	Amount of fluid for 90% recovery (lb)	F/A at 90% air flow recovery	Maximum air flow recovery (lb/hr)	F/A at max. air flow recovery	Time for max. air flow recovery (min)	Remarks
Series G	(See figure 23)																						
45	40	510	.104	250	11.25	200	.240	40	250	Solox D-I	H.R.	40	-	1	6	.3	R	.20	.127	510	.116	1	Mixture went rich. Rapid recovery.
45-A	40	510	.108	250	8.5	200	.330	40	250	Solox D-I	H.R.	60	-	1	5	.6	R	.60	.122	450	.122	.6	Mixture went rich. Rapid recovery.
46	40	2000	.069	250	26	1000	.088	40	250	Solox D-I	H.R.	40	-	1	15	.3	R	.20	.071	1930	.073	.6	Throttling ice, rich mixture, re-icing.
46-A	40	2000	.070	250	39.5	1000	.082	40	250	Solox D-I	H.R.	60	-	1	10	.3	R	.30	.068	2000	.069	.9	Throttling ice, rich mixture, re-icing.
47	40	4000	.069	250	33.0	2000	.037	40	250	Solox D-I	H.R.	40	-	1	14	.8	1.75	.53	.067	3870	.069	3	Re-icing to 3650 lb/hr air flow.
47-A	40	4000	.071	250	20.2	2000	L	40	250	Solox D-I	H.R.	60	-	1	20	.3	.5	.3	.057	3950	.069	.9	Rapid recovery, slight re-icing.
48	40	7170	.103	250	7.5	3500	L	40	250	Solox D-I	H.R.	40	-	1	11	1.3	.95	.88	.097	6770	.098	11	Ice remaining in adapter.
48-A	40	7170	.102	250	6	3500	.080	40	250	Solox D-I	H.R.	60	-	1	11	1.1	.45	1.1	.093	7060	.092	7	Slight ice formation in adapter.
Series H	(See figure 24)																						
49	40	4000	.069	250	24.75	2000	.038	40	250	Solox D-I	H.R.	60	-	3	10	1.0	.85	1.0	.073	7140	.073	8	Rapid recovery of air flow and F/A.
50	40	4000	.070	250	24.75	2000	L	40	250	Solox D-I	H.R.	60	-	4	10	.1	.92	.1	-	4000	.069	1.1	Fluctuation of air flow after 90% recovery. Slight re-icing.
51	40	4000	.069	250	20.0	2000	L	40	250	Solox D-I	H.R.	60	-	5	10	.3	9	.3	.037	4420	.069	1.0	Throttle reopened to more open position. Slight re-icing.
52	40	4000	.077	250	20.0	2000	L	40	250	Solox D-I	H.R.	60	-	6	6	2.2	1.5	2.2	.063	7060	.079	5	Gradual recovery.
Series I	(See figure 25)																						
53	40	4000	.070	250	36.5	2000	.038	40	250	Ethyl	A.N.	46	20	1	16	.8	3.5	.61	.053	3970	.066	12	Moderate recovery. Ice left in adapter.
54	40	4000	.070	250	29.0	2000	.038	40	250	Ethyl	A.N.	35	10	1	20	1.0	6.0	.58	.054	3950	.065	7	Moderate recovery. Ice left in adapter.
55	40	4000	.070	250	19.6	2000	L	40	250	S.D.30	A.N.	29	10	1	16	1.1	4.0	.53	.057	3980	.070	16	Moderate recovery. Ice in adapter.
56	40	3950	.071	250	29.75	2000	.039	40	250	S.D.30	A.N.	44	20	1	16	.6	2.2	.44	.056	3940	.071	12	Complete recovery.
57	40	4000	.070	250	17.0	2100	.037	40	250	Shellacol	A.N.	42	20	1	7	.4	1.0	.28	.055	3980	.069	1.6	Rapid recovery.
Series J	(See figure 26)																						
58	40	4000	.070	250	13.25	2000	L	40	250	Isopropyl	W.S.N.		-	1	6	2.0	4.0	.98	.047	3950	.065	3.5	Slow recovery of air flow and mixture ice in adapter.
59	40	4000	.070	250	14.5	2000	L	40	0	Isopropyl	W.S.N.			1	7	2.2	3.0	1.20	.054	4000	.066	5.0	Slow recovery.
Series K	(See figure 27)																						
60						3850	.052	40	250	Solox D-I	H.R.	10	-	1	30								Minimum air flow 2150 lb/hr at 30 min. Throttle frozen stuck.
61						4000	.071	40	250	Solox D-I	H.R.	20	-	1	14								Minimum air flow 2000 lb/hr. Throttle stuck.
62						3950	.068	40	250	Solox D-I	H.R.	30	-	1	30								Minimum air flow 3000 lb/hr at 18 min.
63						4050	.070	40	250	Solox D-I	H.R.	40	-	1	30								Minimum air flow 3200 lb/hr at 26 min.
64						4000	.068	40	250	Solox D-I	H.R.	50	-	1	30								Minimum air flow 3870 lb/hr at 16 min.
65						4000	.070	40	250	Solox D-I	H.R.	60	-	1	20								No icing.
66						4000	.071	40	250	Solox D-I	H.R.	80	-	1	20								Fluctuations, no apparent icing.
61-A						4000	.073	40	250	Isopropyl	H.R.	20	-	1	30								Minimum air flow 3400 lb/hr at 30 min.
62-A						4000	.073	40	250	Isopropyl	H.R.	30	-	1	32								Minimum air flow 3850 lb/hr at 20 min.
Series L	(See figure 28)																						
67	25	4200	.067	250	2.25	2060	.136	25	250	Isopropyl	A.N.	42	20	1	10	1.8	R	1.26	.070	3880	.070	9	Mixture went rich on icing.
68	25	4220	.065	250	1.75	2100	R	25	250	Solox D-I	H.R.	60	-	1	10	-	R	-	-	2850	.102	9	Very incomplete recovery.
69	25	4200	.067	250	2.25	2060	.159	25	250	Solox D-I	H.R.	80	-	1	10	-	R	-	-	2740	.104	.8	Very incomplete recovery.
70	25	4200	.070	250	2.0	2070	R	25	250	Solox D-I	M.H.R.	80	12	1	7	1.0	R	1.33	.075	4100	.074	5	Moderate recovery.
71	25	4000	.067	250	3.0	2100	.193	85	250	-	-	-	-	1	5	.8	R	-	.077	3900	.073	1.1	Rapid and complete recovery.
Series M	(See figure 33)																						
72	40	4000	.070	250	21.5	2000	.042	50	0	-	-	-	-	1	3	-	-	-	-	-	-	-	Air flow fell off to zero.
73	40	4000	.070	250	11.5	2000	.043	60	0	-	-	-	-	1	10	3.5	5.0	-	.064	3810	.065	10	Slow recovery, ice remaining in adapter.
74	40	4000	.070	250	16.0	2000	.042	65	0	-	-	-	-	1	8	1.3	2.7	-	.055	3800	.065	3	Slight re-icing. Ice in adapter.
75	40	4000	.070	250	14.5	2000	.039	70	0	-	-	-	-	1	9	3.0	4.0	-	.061	3800	.065	5	Ice remaining in adapter.
76	40	4000	.070	250	13	2000	.041	80	0	-	-	-	-	1	10	.4	.7	-	.057	3860	.069	4	Lump of ice left in adapter.
77	40	4050	.069	250	17.25	2000	L	95	0	-	-	-	-	1	10	.9	.9	-	.065	3850	.065	.9	Moderate recovery.
78	40	4000	.069	250	18	2000	L	110	0	-	-	-	-	1	6	.3	.5	-	.058	3810	.066	.6	Rapid recovery.
79	40	4000	.071	250	14.5	2000	L	125	0	-	-	-	-	1	5	.4	.5	-	.058	3800	.072	.8	Rapid recovery.
80	40	4000	.070	250	13	2000	L	140	0	-	-	-	-	1	6	.4	.7	-	.049	3820	.069	.8	Rapid recovery.
Series N	(See figure 34)																						
81	40	4000	.070	250	17	2000	.042	50	250	-	-	-	-	1	1.6	-	-	-	-	-	-	-	Continued icing until air flow dropped to zero.
82	40	4000	.069	250	19	2000	.040	60	250	-	-	-	-	1	11.0	.6	1.45	-	.060	3920	.066	1.5	Re-icing to 3180 lb/hr air flow.
83	40	4000	.070	250	15	2000	.040	65	250	-	-	-	-	1	10	1.8	2.7	-	.059	3900	.070	4.0	Slow but complete recovery.
84	40	4000	.070	250	19.75	2000	.037	70	250	-	-	-	-	1	10	.7	1.8	-	.059	3900	.068	4	Complete recovery.
85	40	4000	.069	250	12	2000	L	80	250	-	-	-	-	1	6	.7	.94	-	.056	3880	.068	1.1	Complete recovery.
86	40	4000	.070	250	19.25	2000	.056	95	250	-	-	-	-	1	6	.3	.5	-	.060	3780	.075	1.2	Rapid complete recovery.

[3]1 - Throttle left at original setting throughout de-icing.
2 - Throttle opened wide at start of de-icing.
3 - De-icing fluid turned on; throttle left at original setting until air flow had recovered to 3500 lb/hr; when air flow had recovered to 3500 lb/hr the throttle was opened wide.
4 - De-icing fluid turned on; throttle closed and reopened to cruising several times in first 10 sec.
5 - De-icing fluid turned on; throttle completely closed for first 10 sec. and then reopened to cruising position.
6 - De-icing fluid turned on; throttle opened in successive steps at 5 sec. intervals from 22° to 37°, 37° to 50°, and 50° to wide open.

[4]R - Mixture went rich.

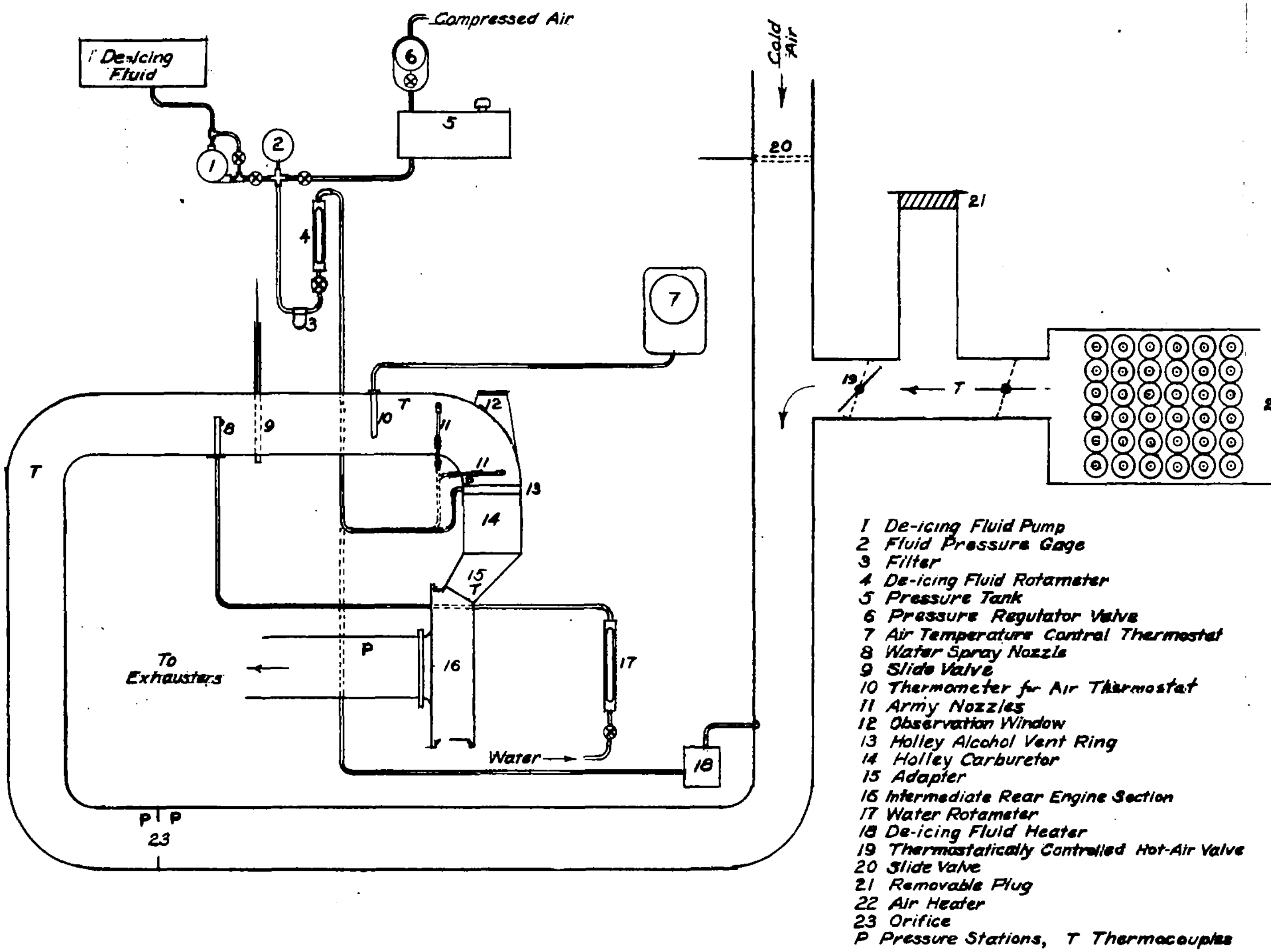


Figure 1. Schematic Diagram of Induction System De-Icing Test Apparatus

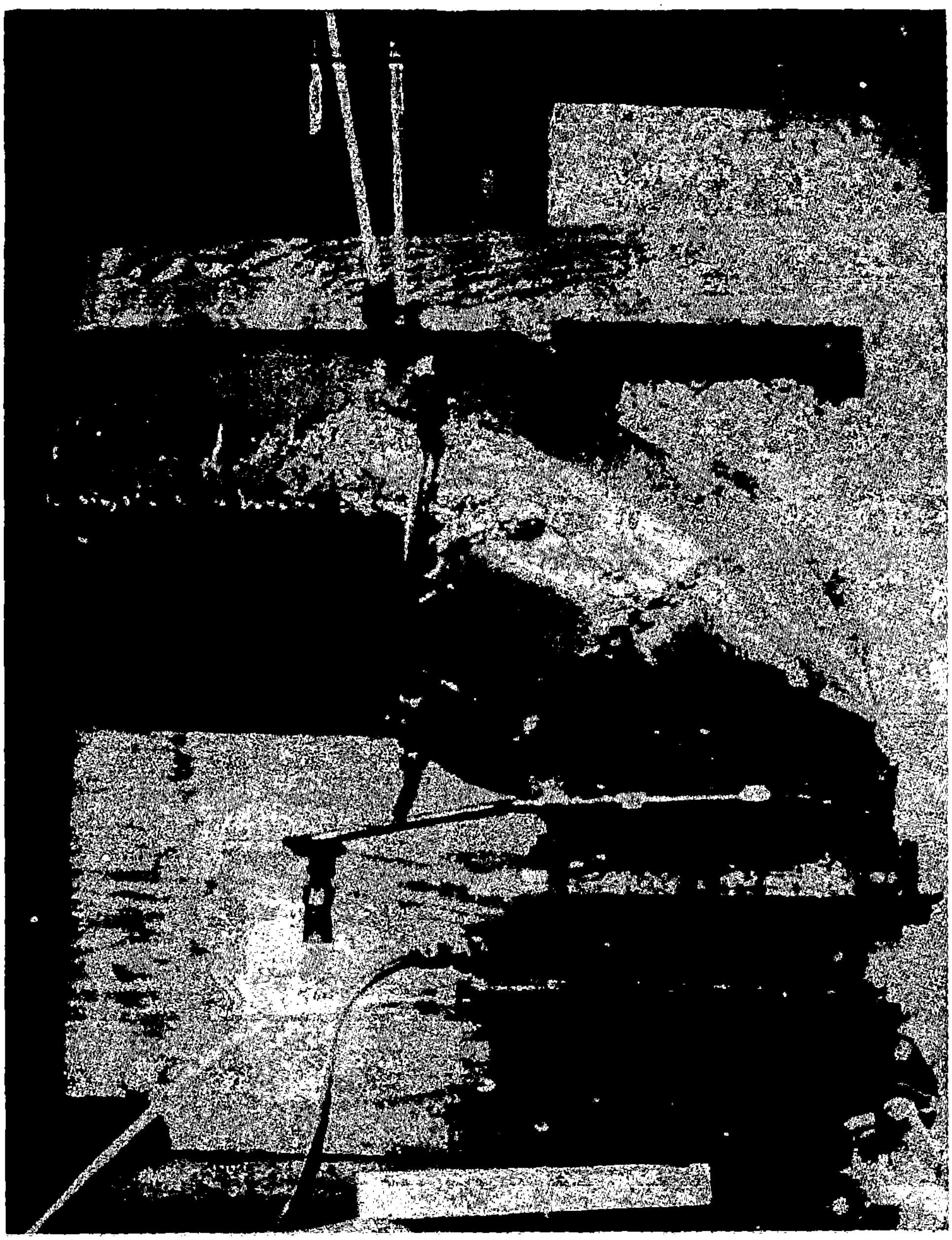
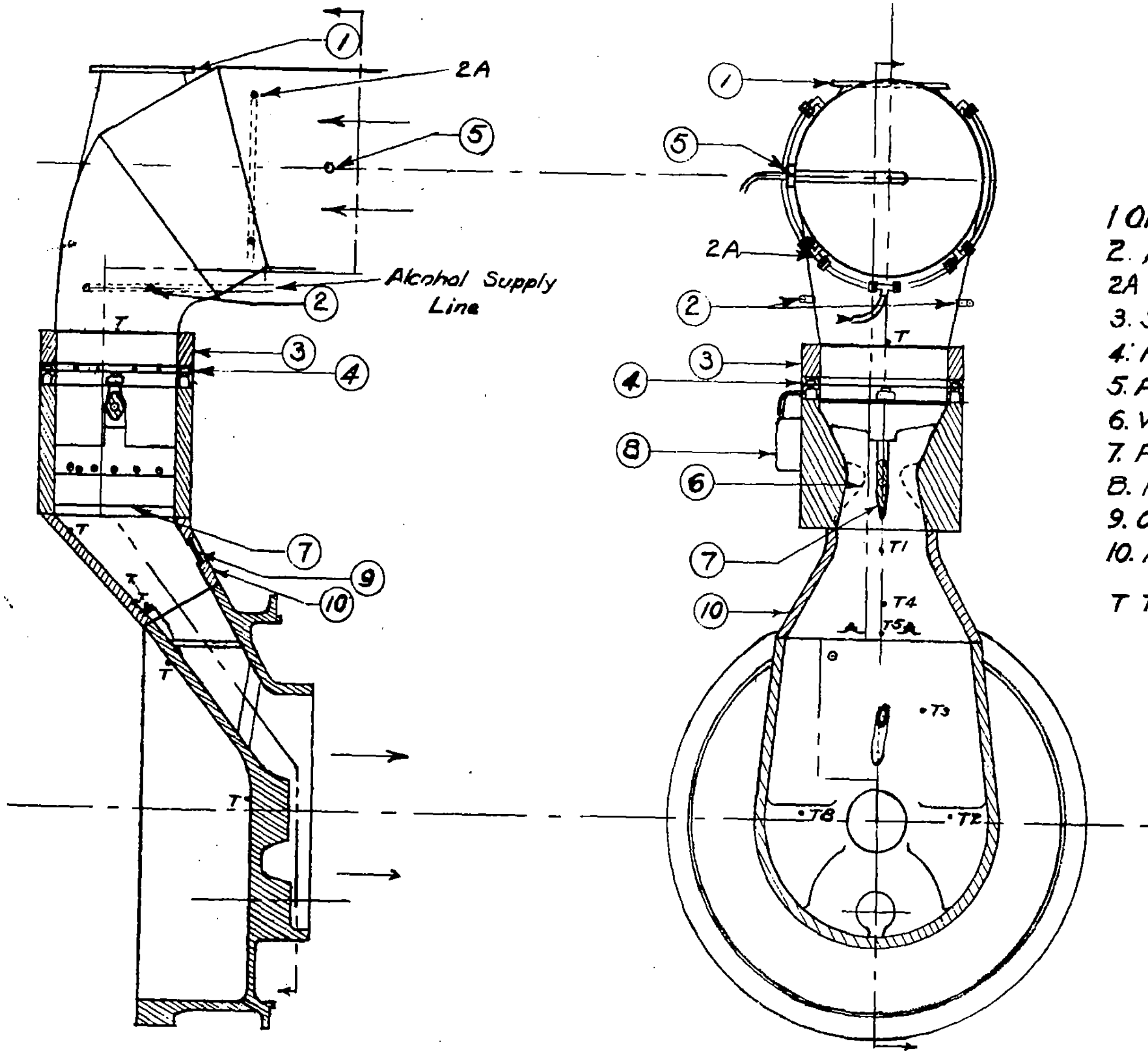


Figure 2.- Carburetor and air scoop showing observation window and Army nozzle locations.



1 Observation Window
2. Army Nozzles
2A Army Nozzles (Alternate Location)
3. Static Ring
4. Holley Alcohol Ring
5. Pressure Bulb Thermometer for Air Thermostat
6. Variable Venturi
7. Fuel Nozzle Bar
8. Mixture Control
9. Observation Window
10. Adapter

T Thermocouple Stations

Figure 3 Schematic Diagram of Induction System

NACA

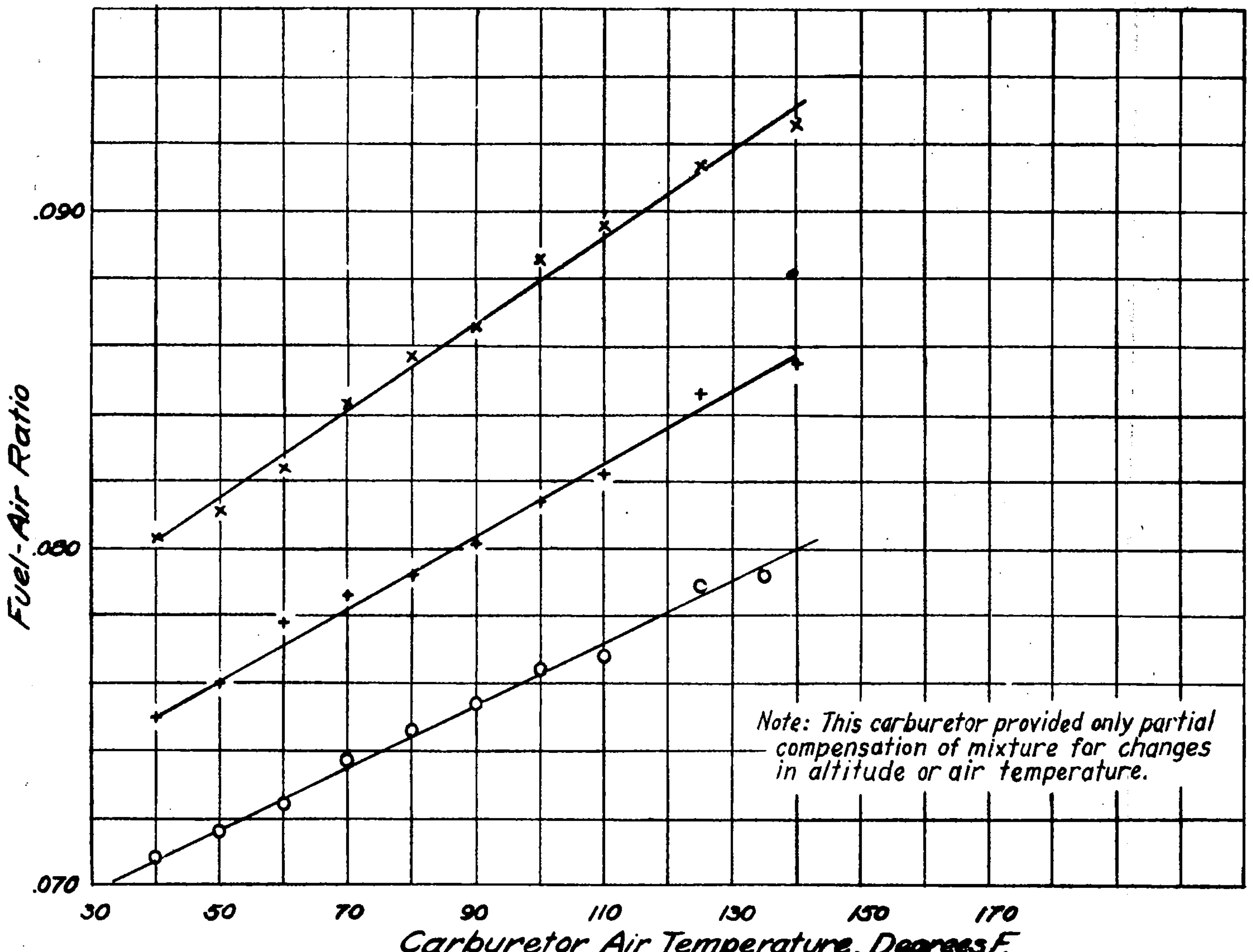


Figure 4 Effect of Carburetor Air Temperature on Fuel/Air Ratio
Holley Carburetor 1375-F, Fuel Temperature 46°F

Fig. 4

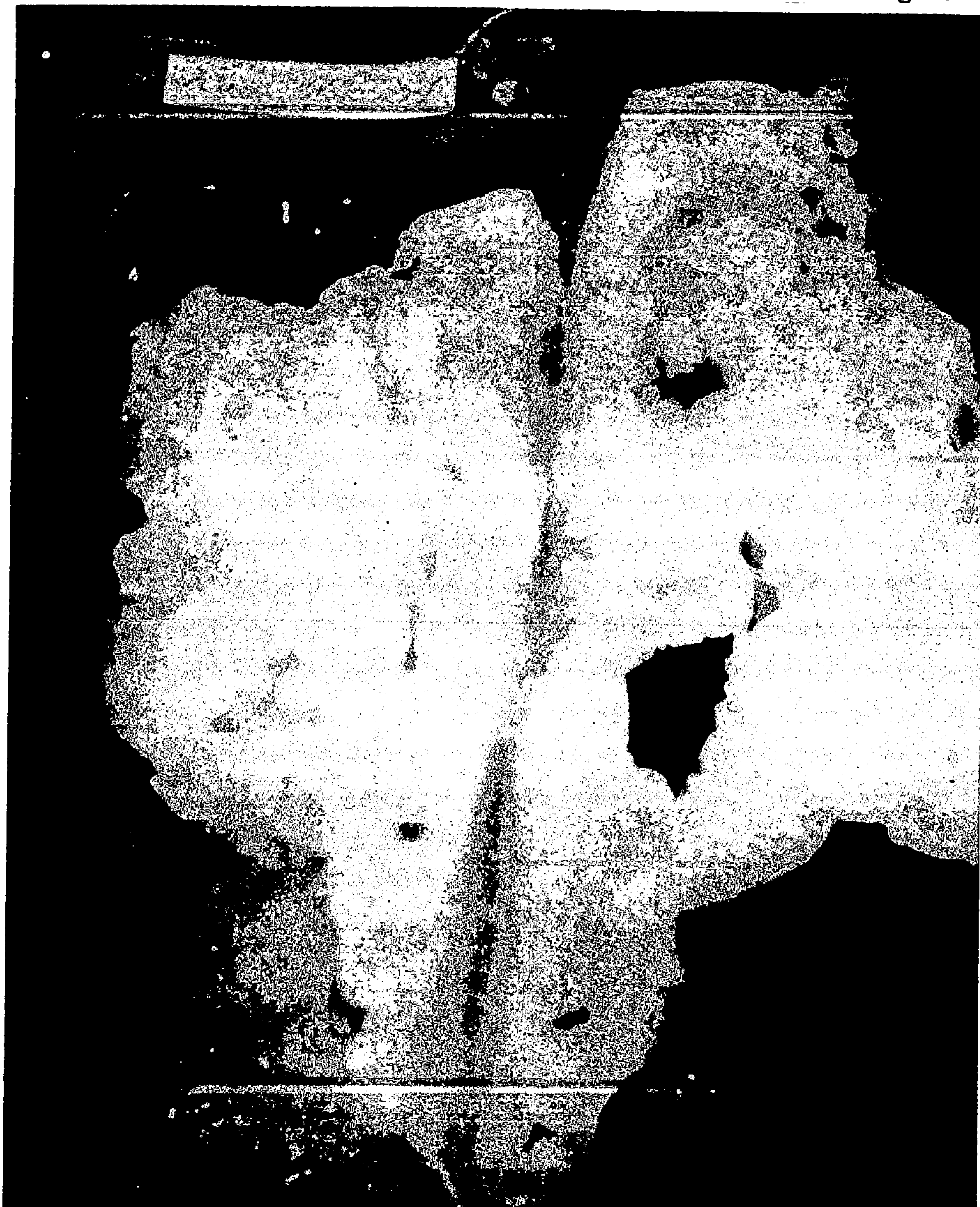


Figure 5.- Typical refrigeration ice formation in carburetor adapter.

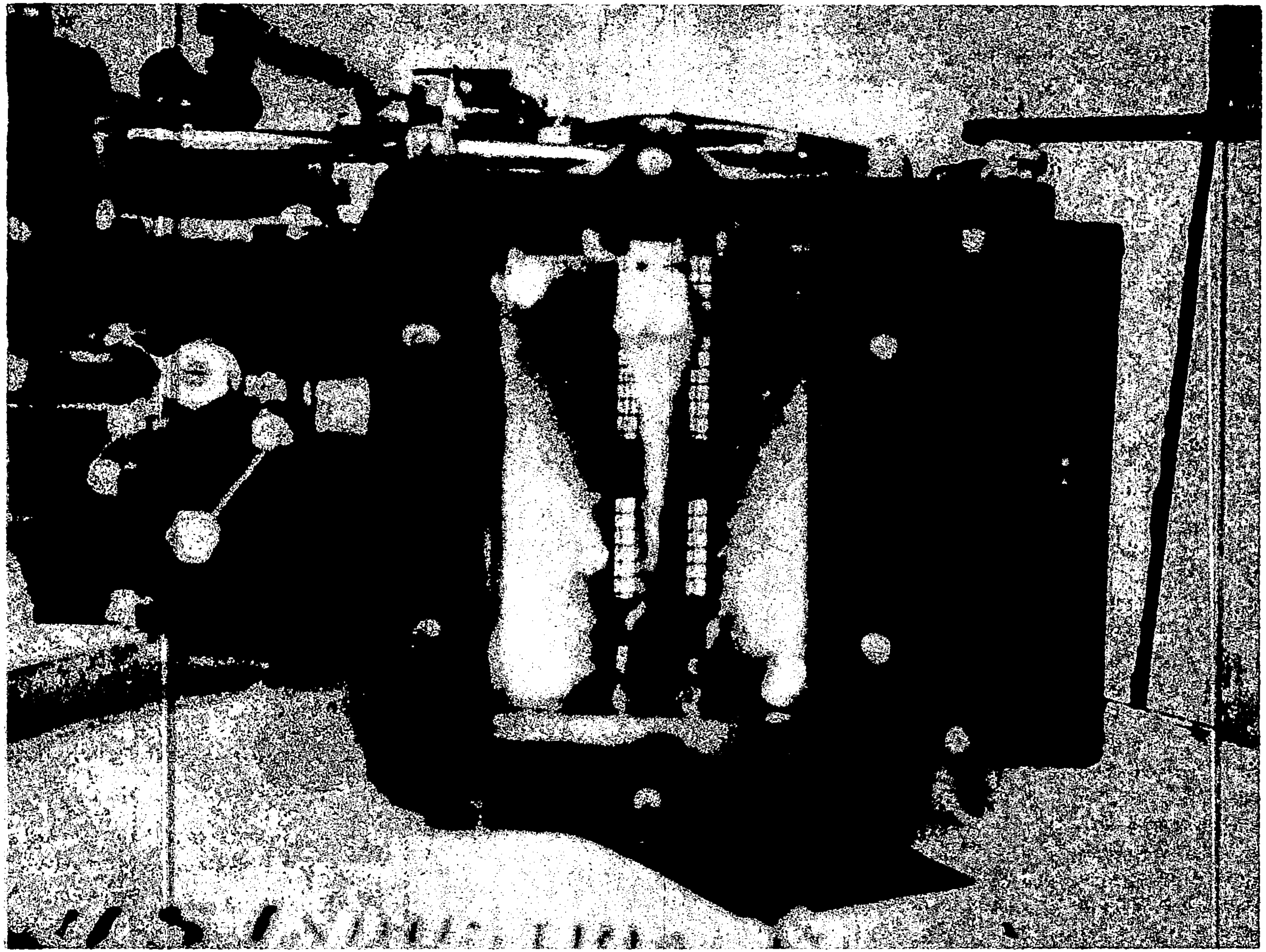


Figure 6.- Impact ice formation on fuel nozzle bar and in venturis resulting from low temperature operation.

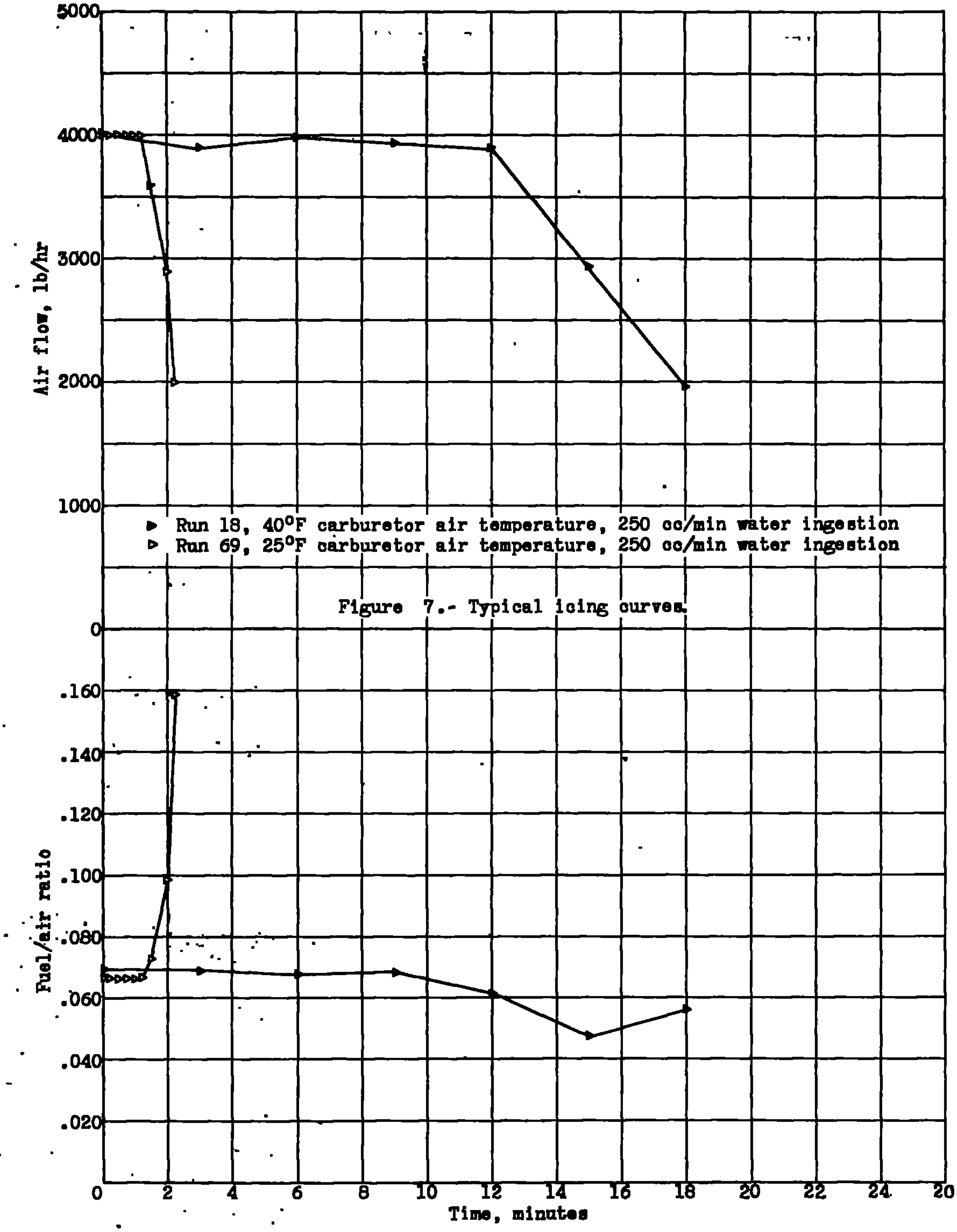


Figure 7.- Typical icing curves.

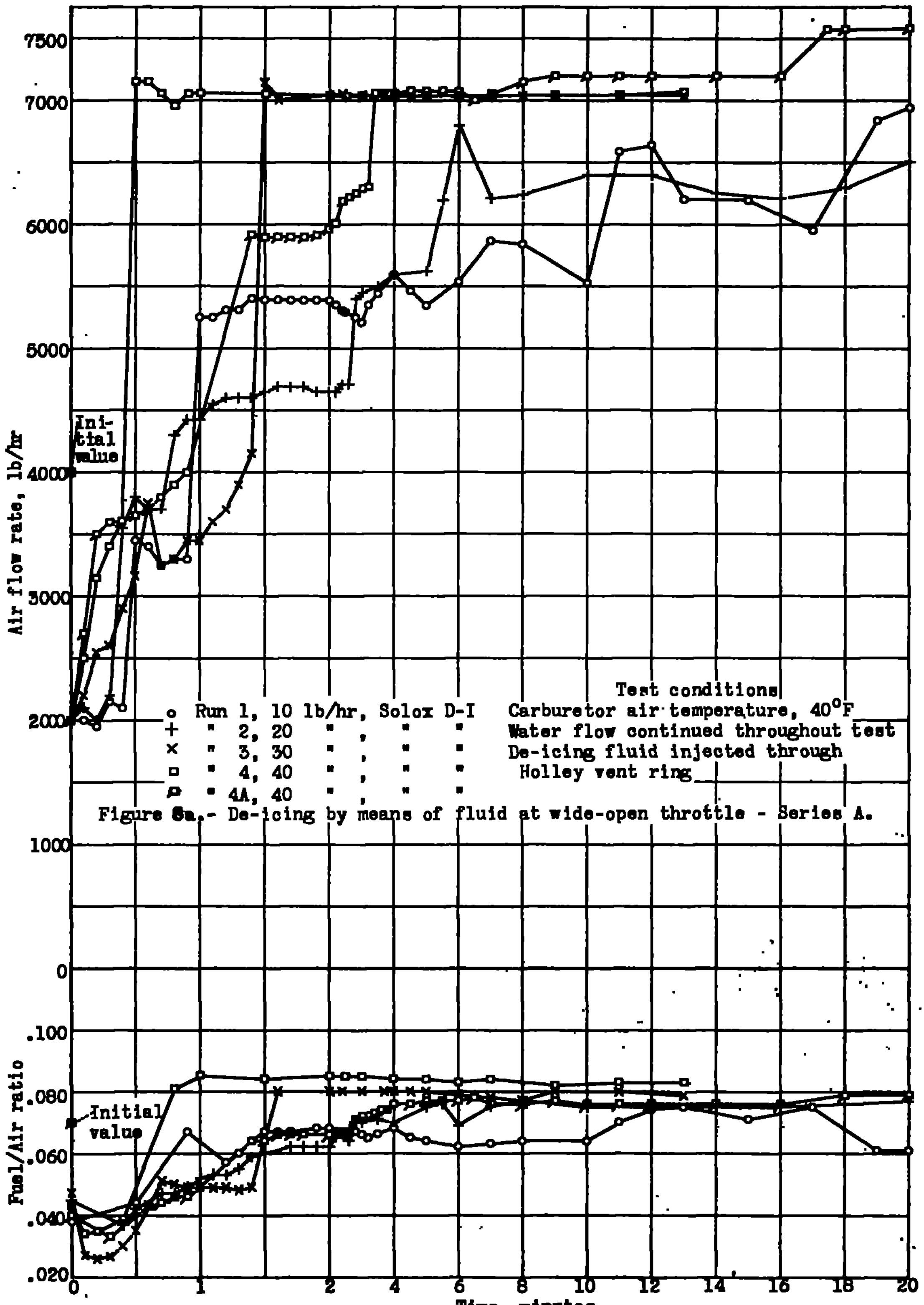


Figure 8a.- De-icing by means of fluid at wide-open throttle - Series A.

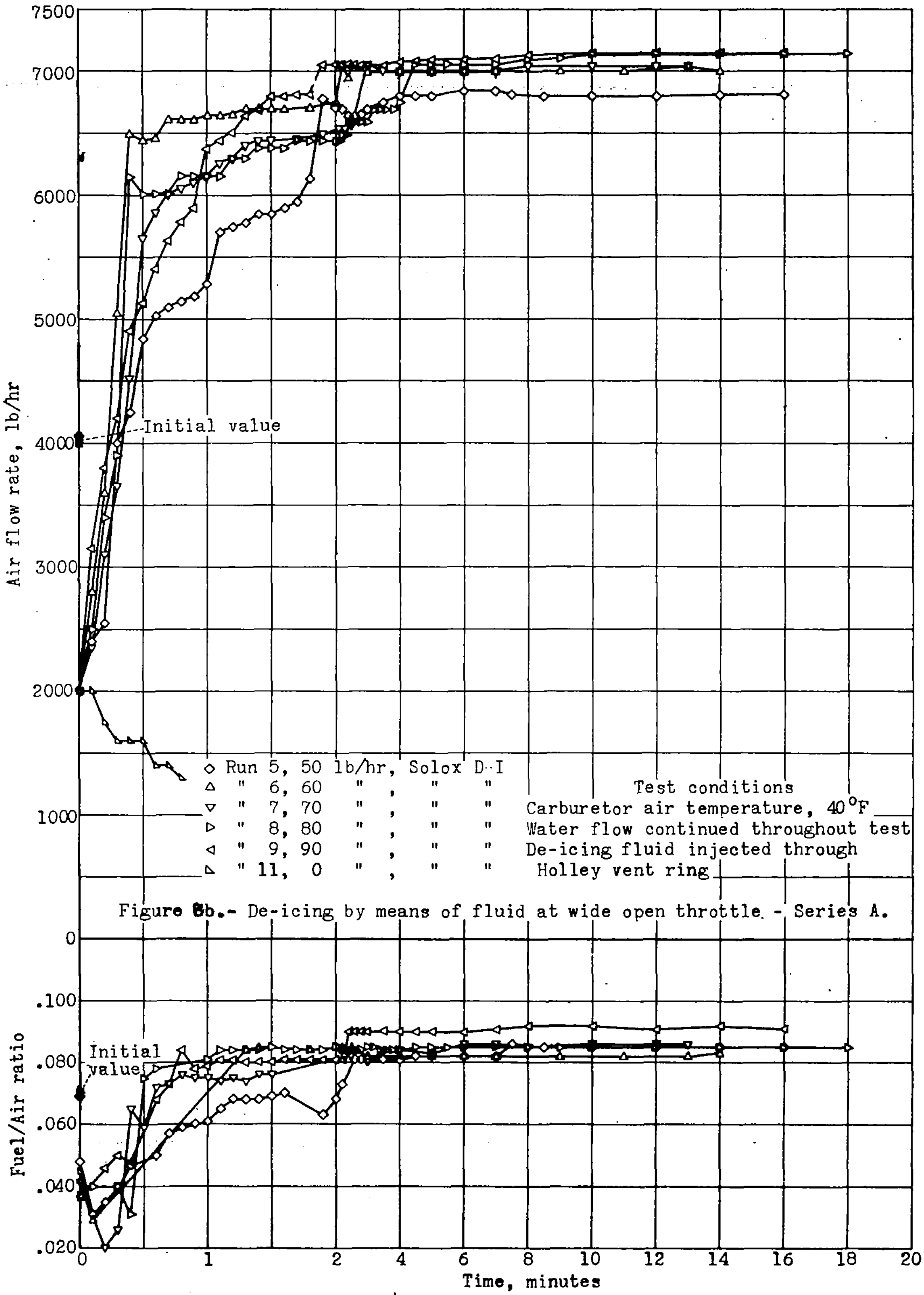


Figure 8b.- De-icing by means of fluid at wide open throttle. - Series A.

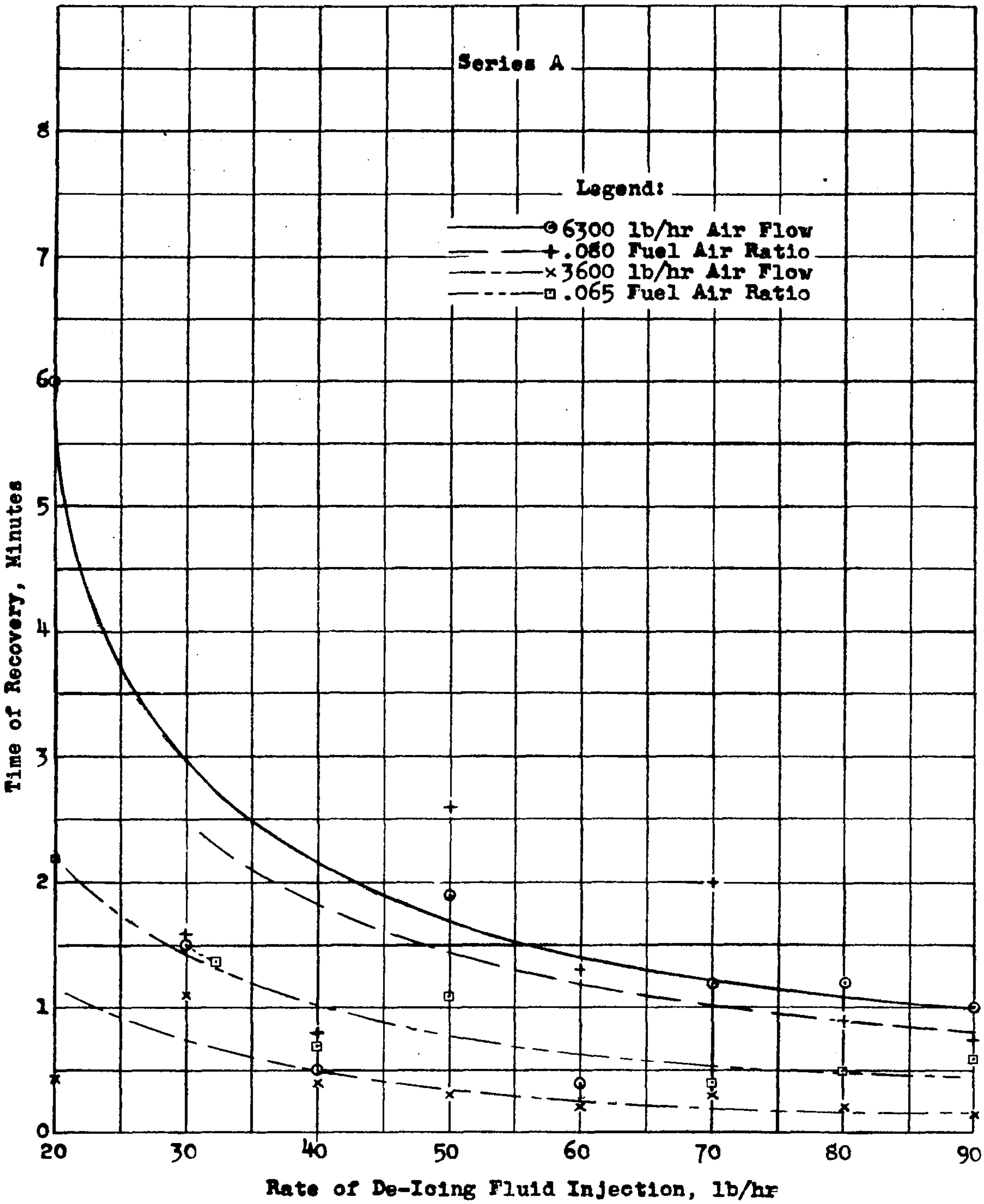


Figure 9.- Effect of De-Icing Fluid Flow Rate on Recovery of Air Flow and Fuel Air Ratio; Standard Holley Ring; Solox D-I.

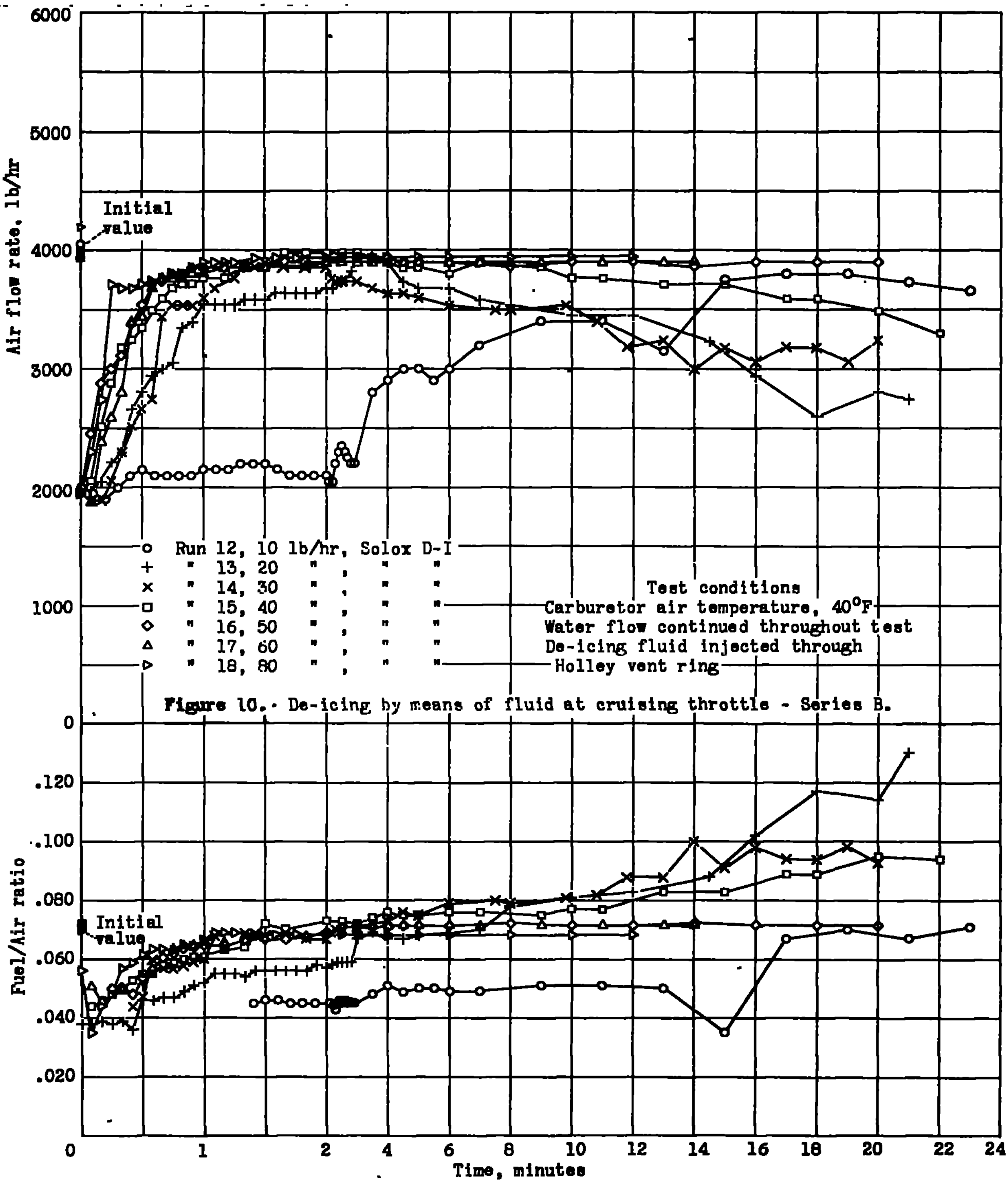


Figure 10.- De-icing by means of fluid at cruising throttle - Series B.

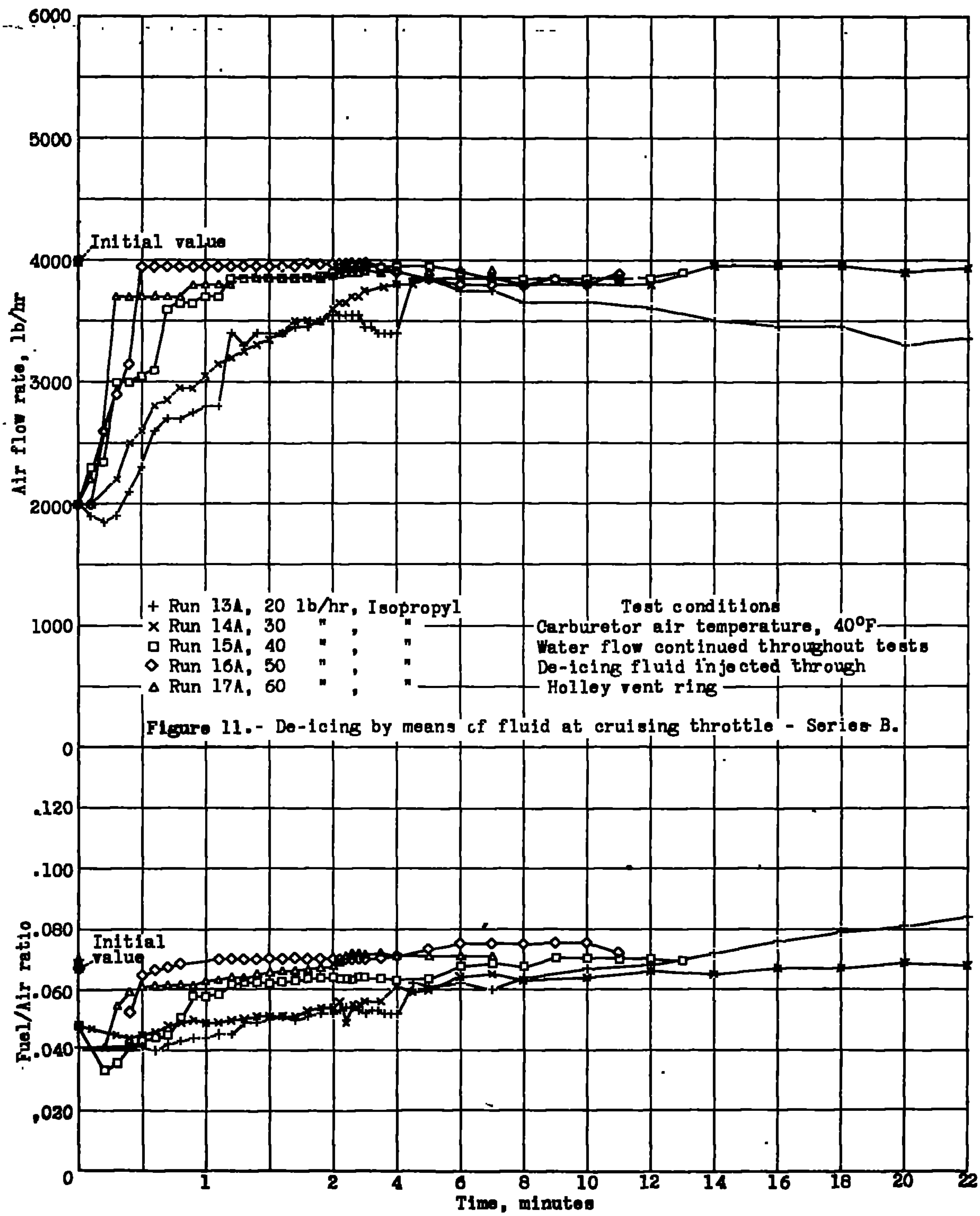


Figure 11.- De-icing by means of fluid at cruising throttle - Series B.

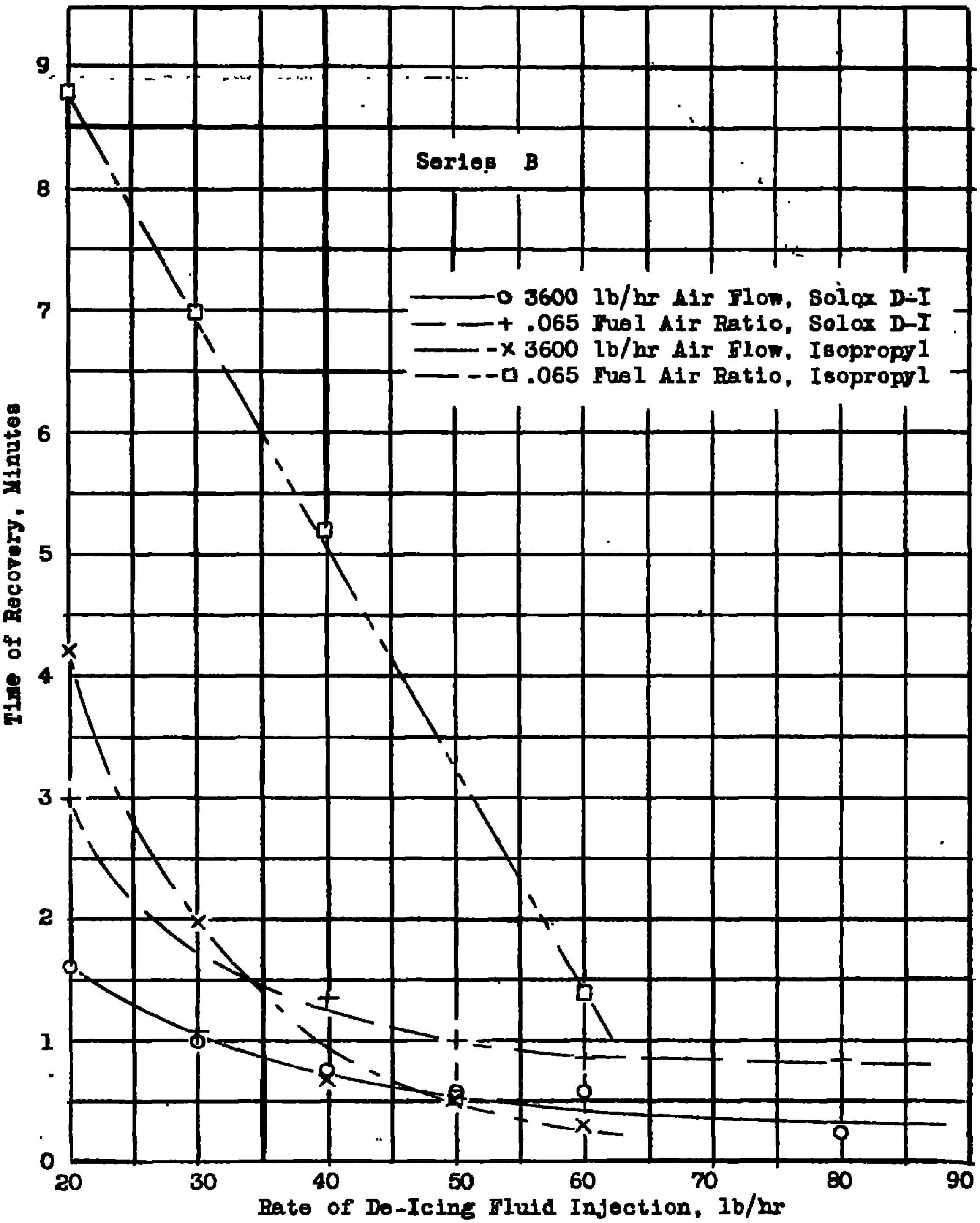


Figure 12.- Effect of De-Icing Fluid Flow Rate on Reccvery of Air Flow And Fuel Air Ratio; Standard Holley Ring.

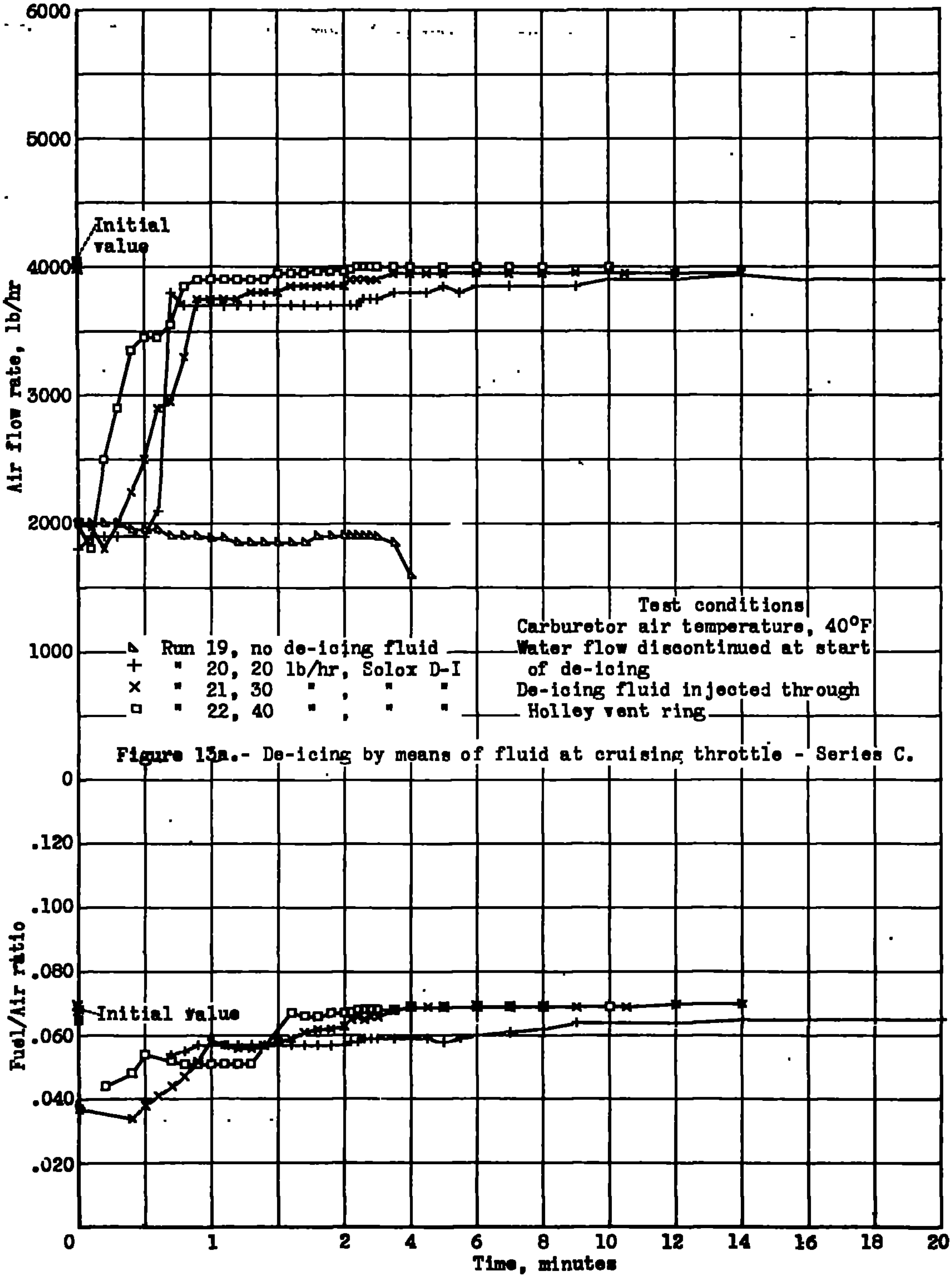


Figure 13a.- De-icing by means of fluid at cruising throttle - Series C.

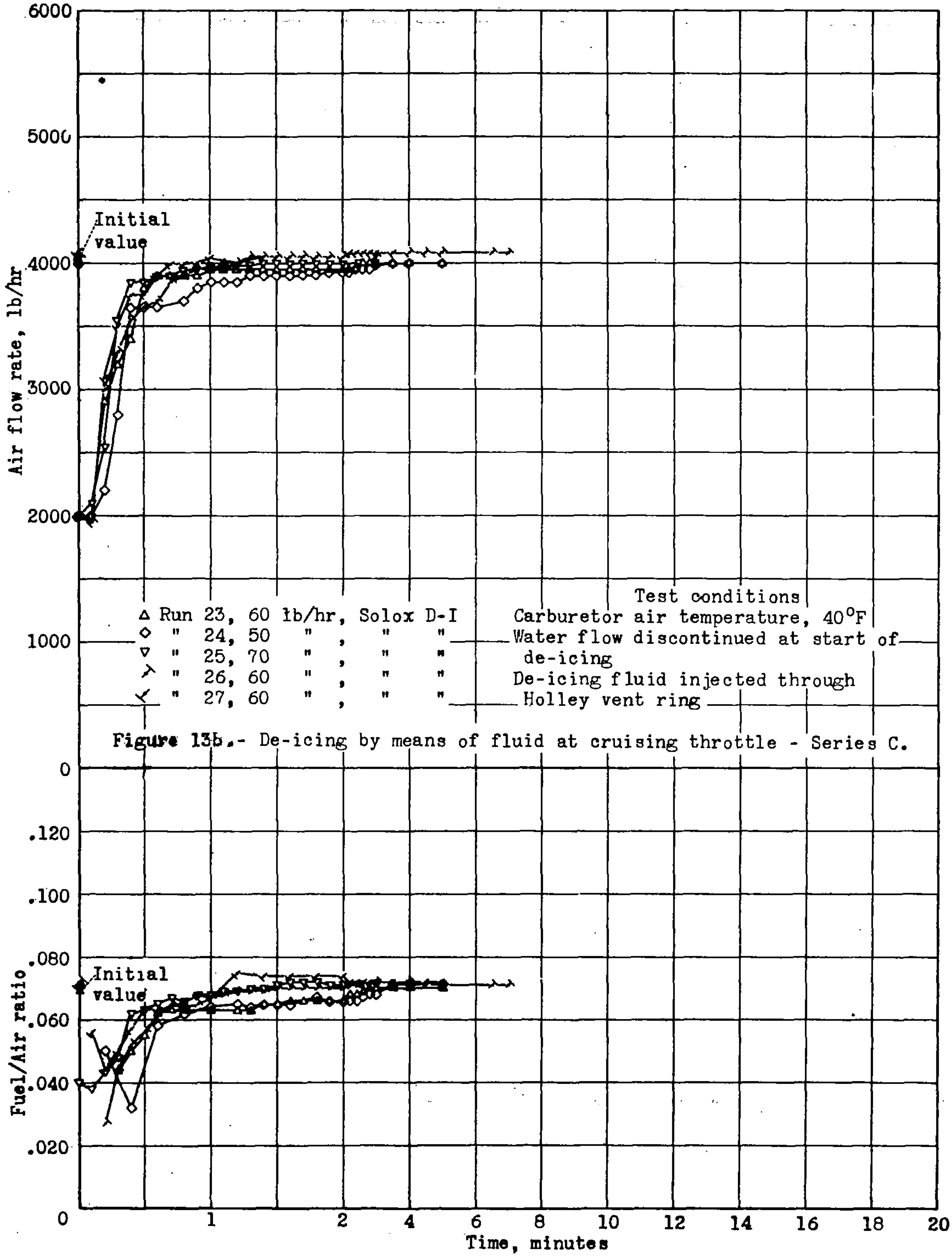


Figure 13b.- De-icing by means of fluid at cruising throttle - Series C.

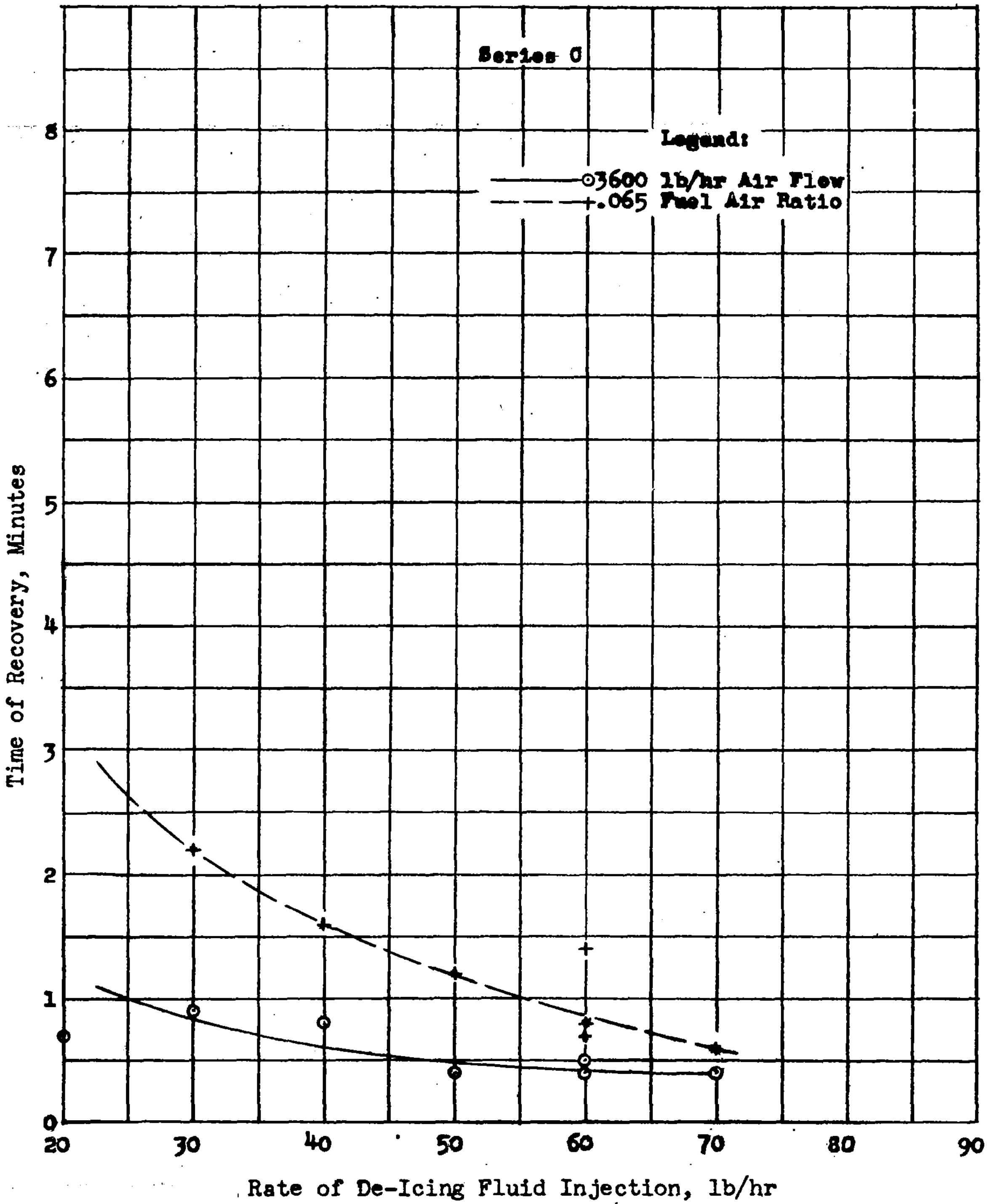


Figure 14- Effect of De-Icing Fluid Flow Rate on Recovery of Air Flow and Fuel Air Ratio; Std. Holley Ring; Solox D-I; Water off During De-Icing.

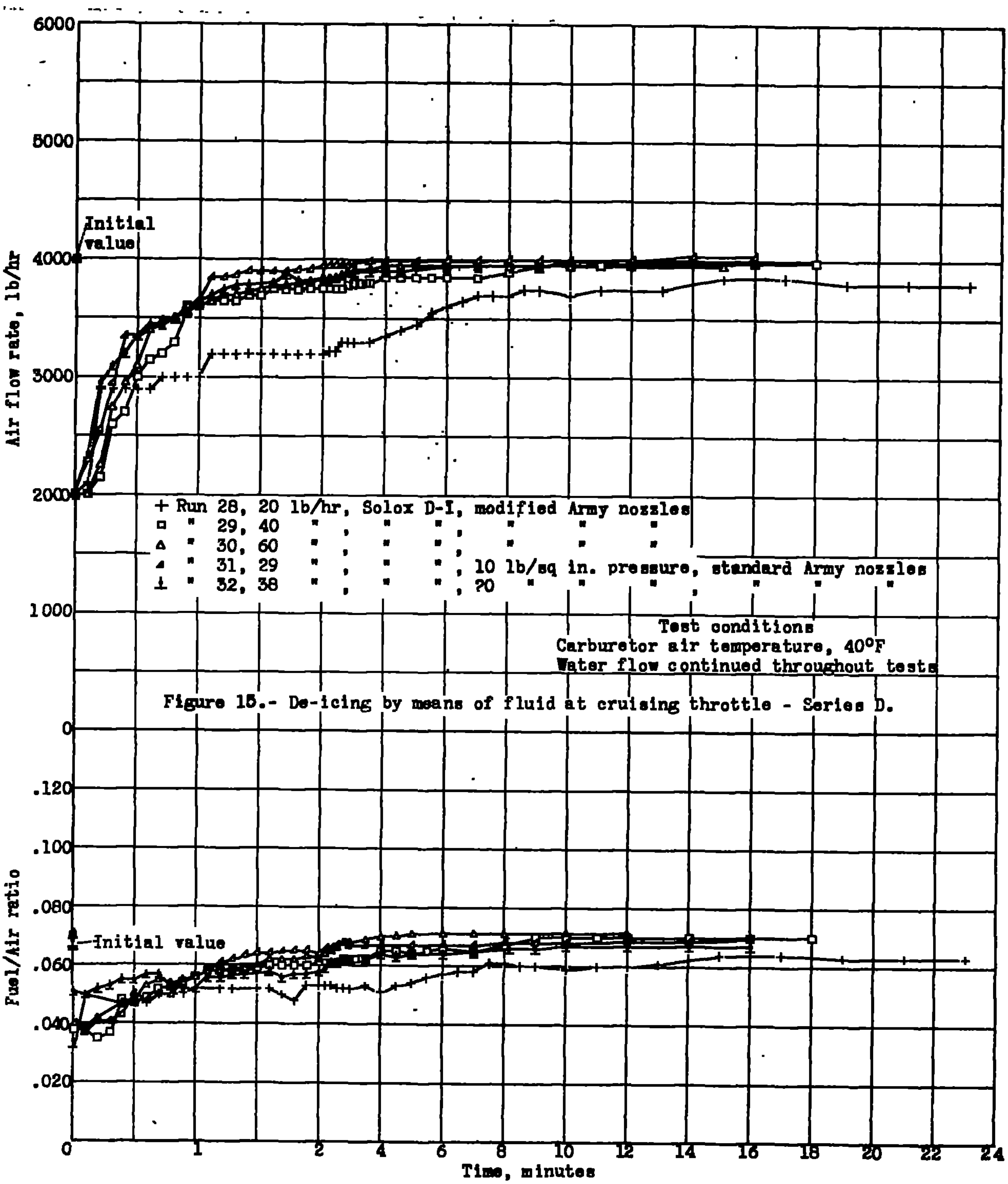


Figure 15.- De-icing by means of fluid at cruising throttle - Series D.

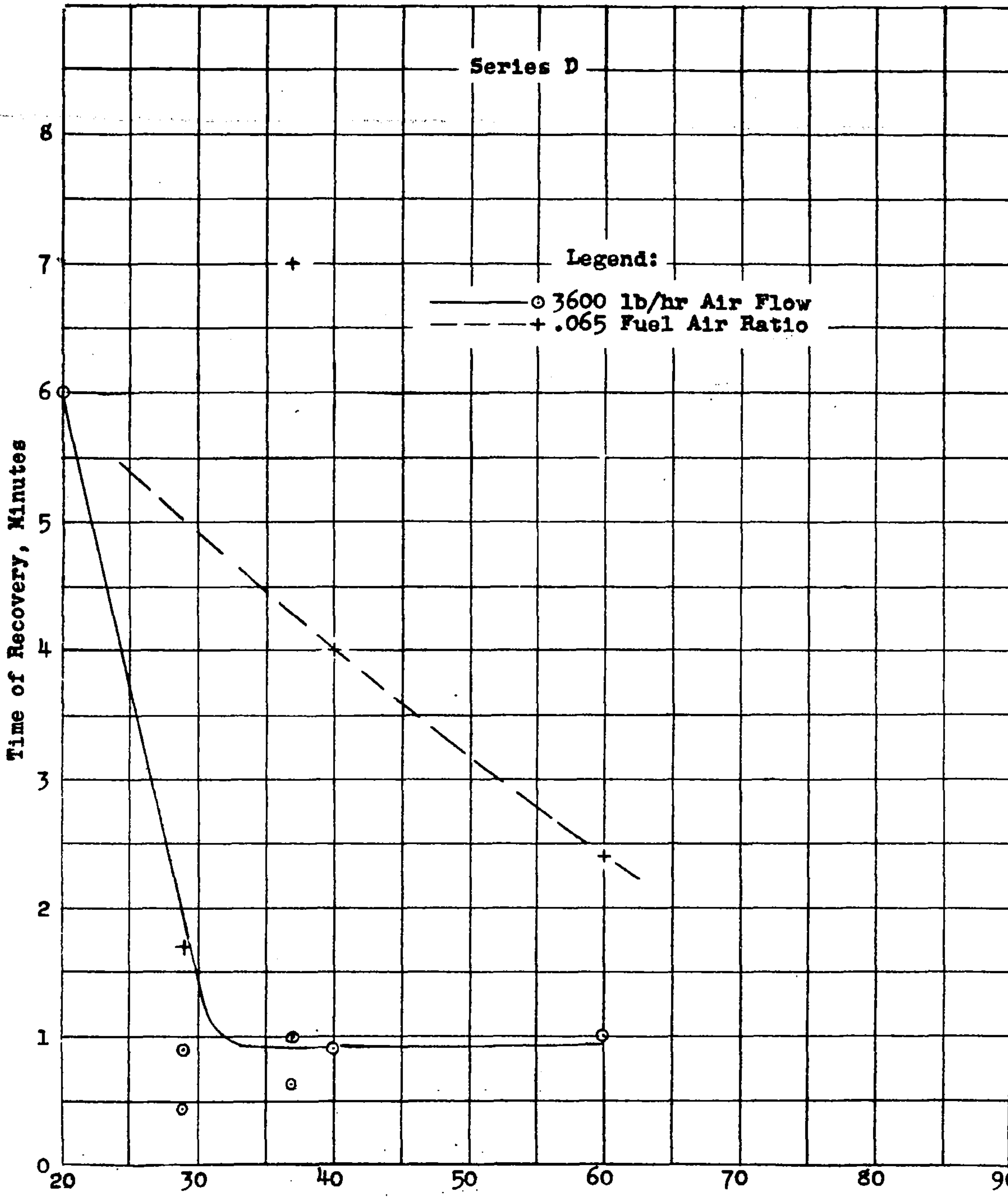


Figure 16.- Effect of De-Icing Fluid Flow Rate on Recovery of Air Flow and Fuel Air Ratio; Solox D-I; Standard & Modf. Army Nozzles

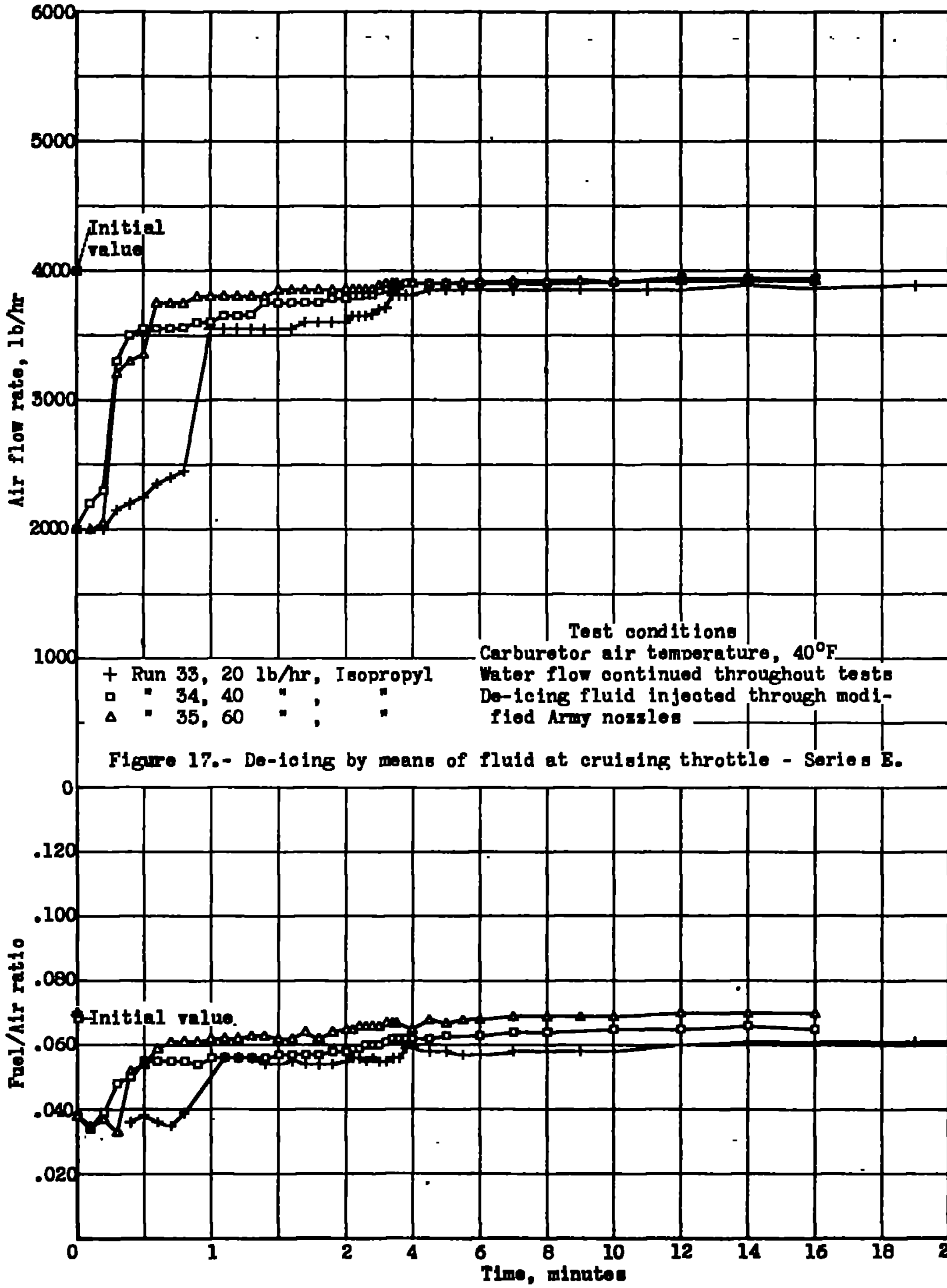


Figure 17.- De-icing by means of fluid at cruising throttle - Series E.

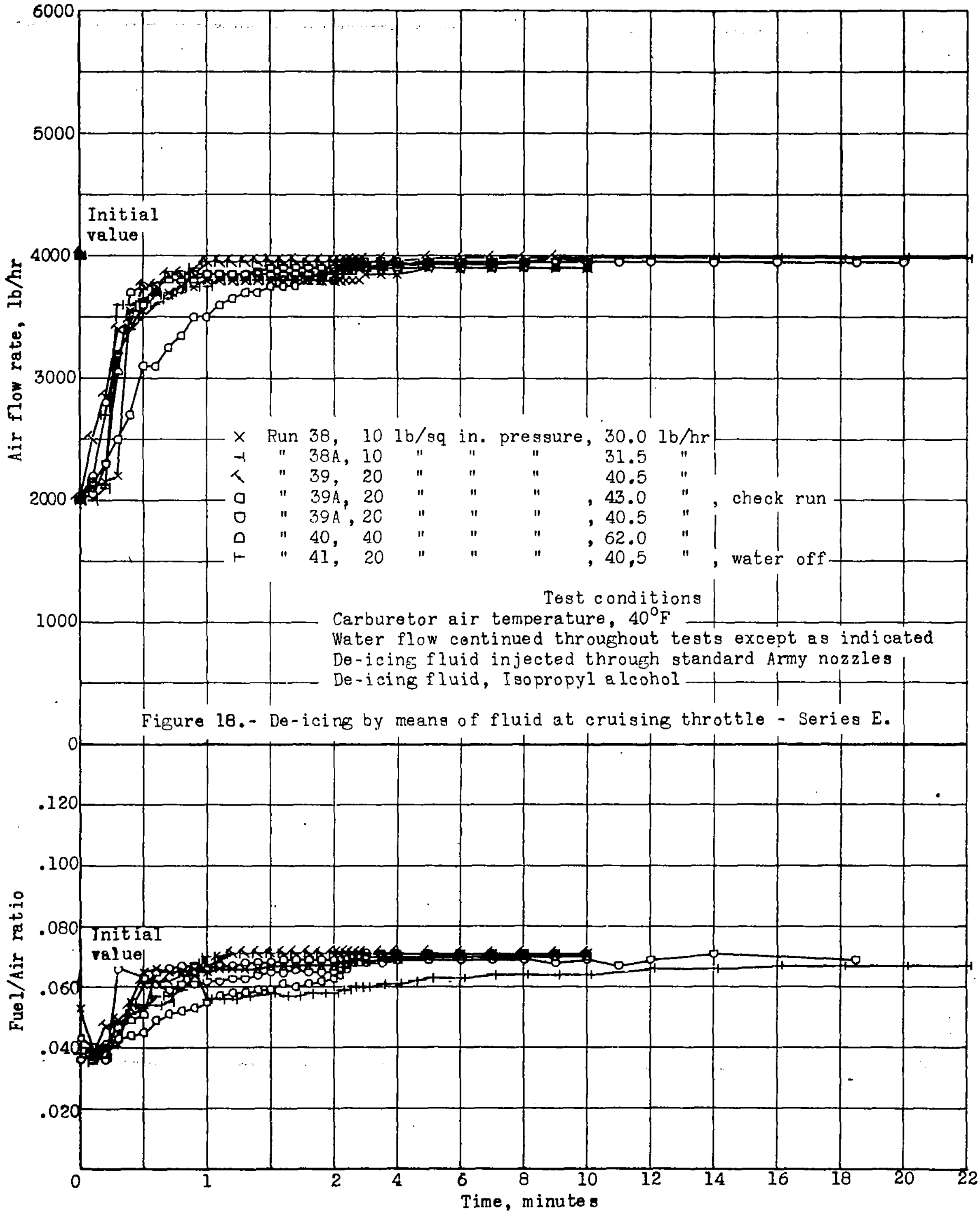


Figure 18.- De-icing by means of fluid at cruising throttle - Series E.

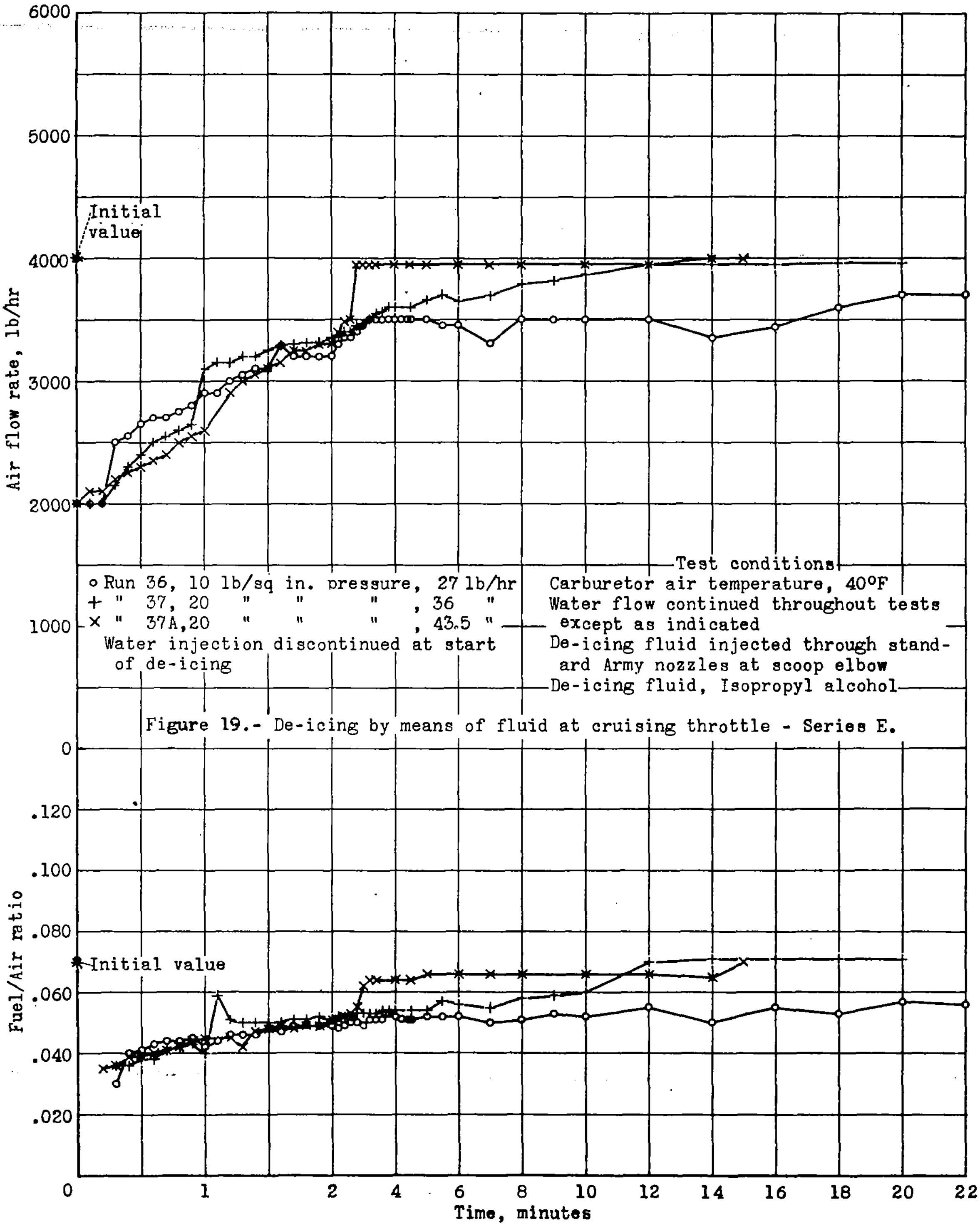


Figure 19.- De-icing by means of fluid at cruising throttle - Series E.

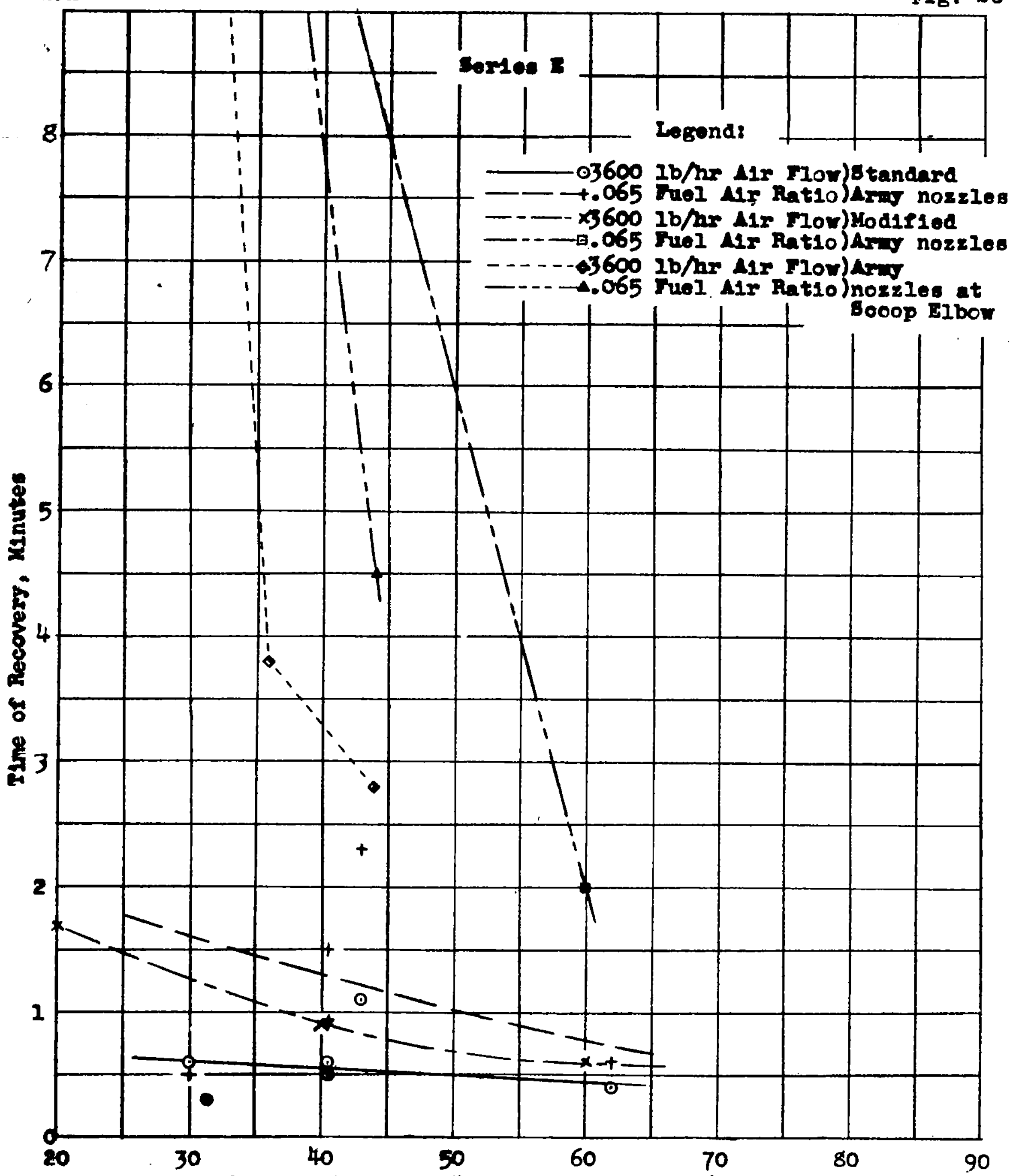


Figure 20.-Effect of De-Icing Fluid Flow Rate on Recovery of Air Flow and Fuel Air Ratio; Isopropyl Alcohol.

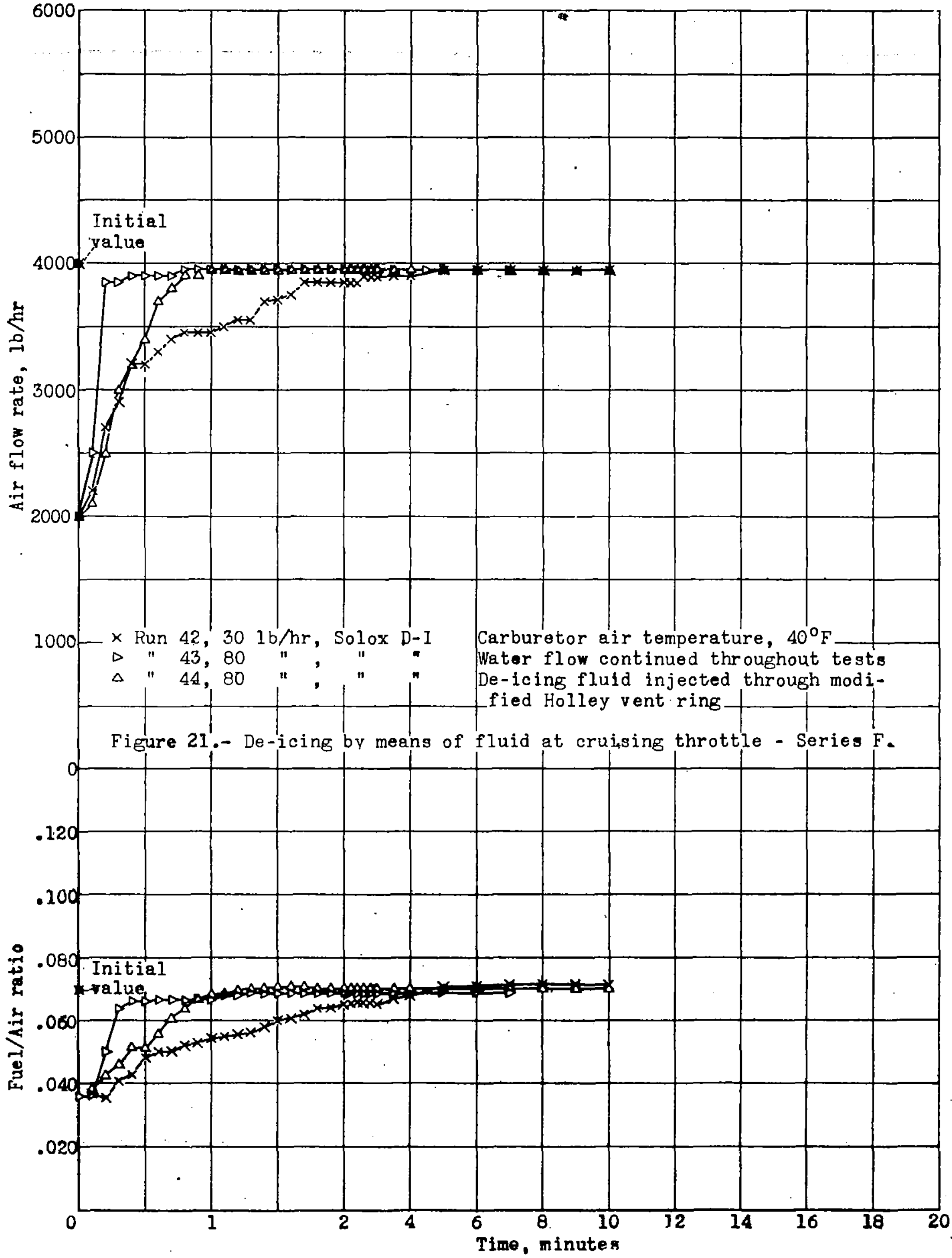


Figure 21.- De-icing by means of fluid at cruising throttle - Series F.

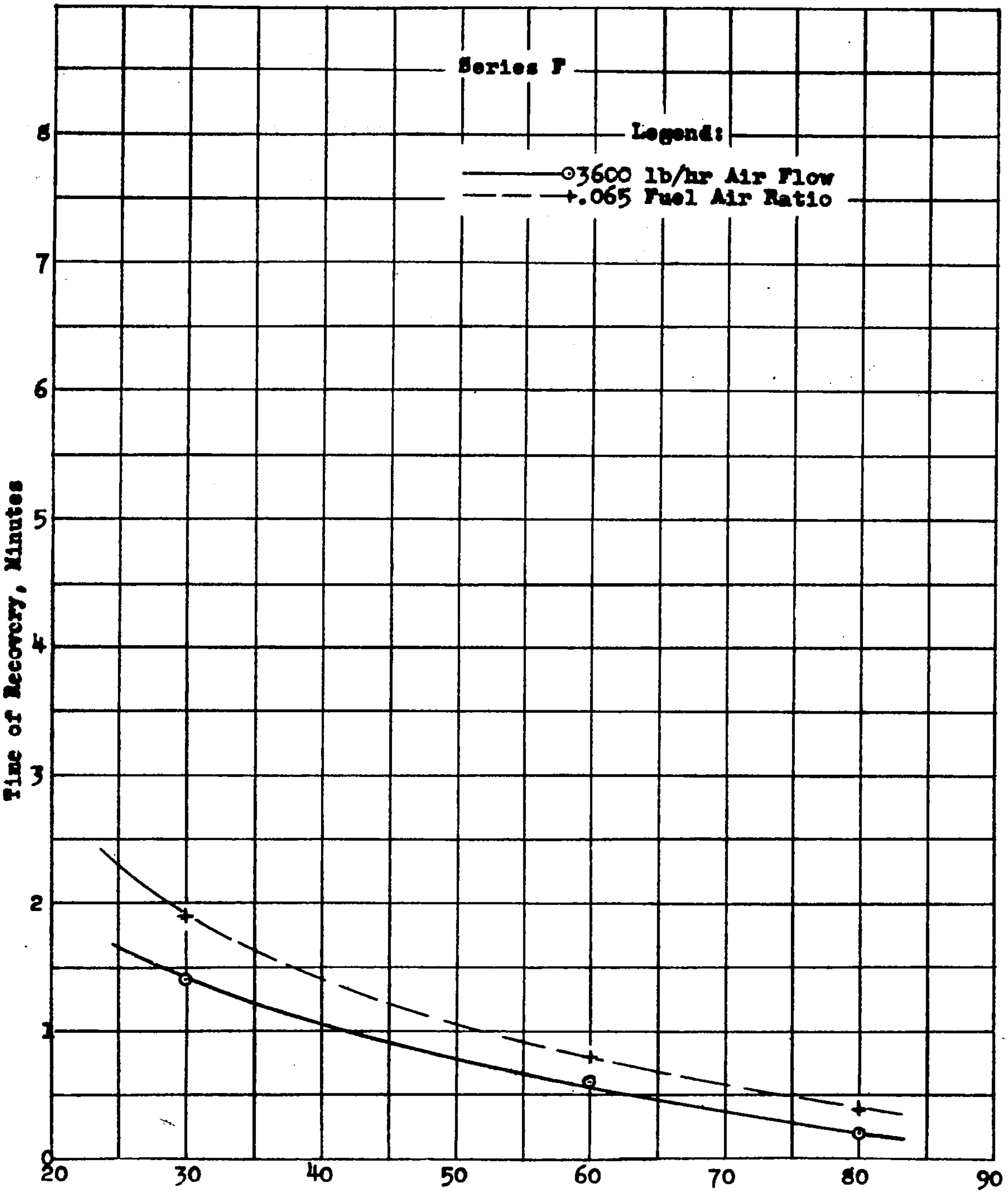


Figure 22.- Effect of De-Icing Fluid Flow Rate on Recovery of Air Flow and Fuel Air Ratio; Modified Holley Ring; Solox D-I.

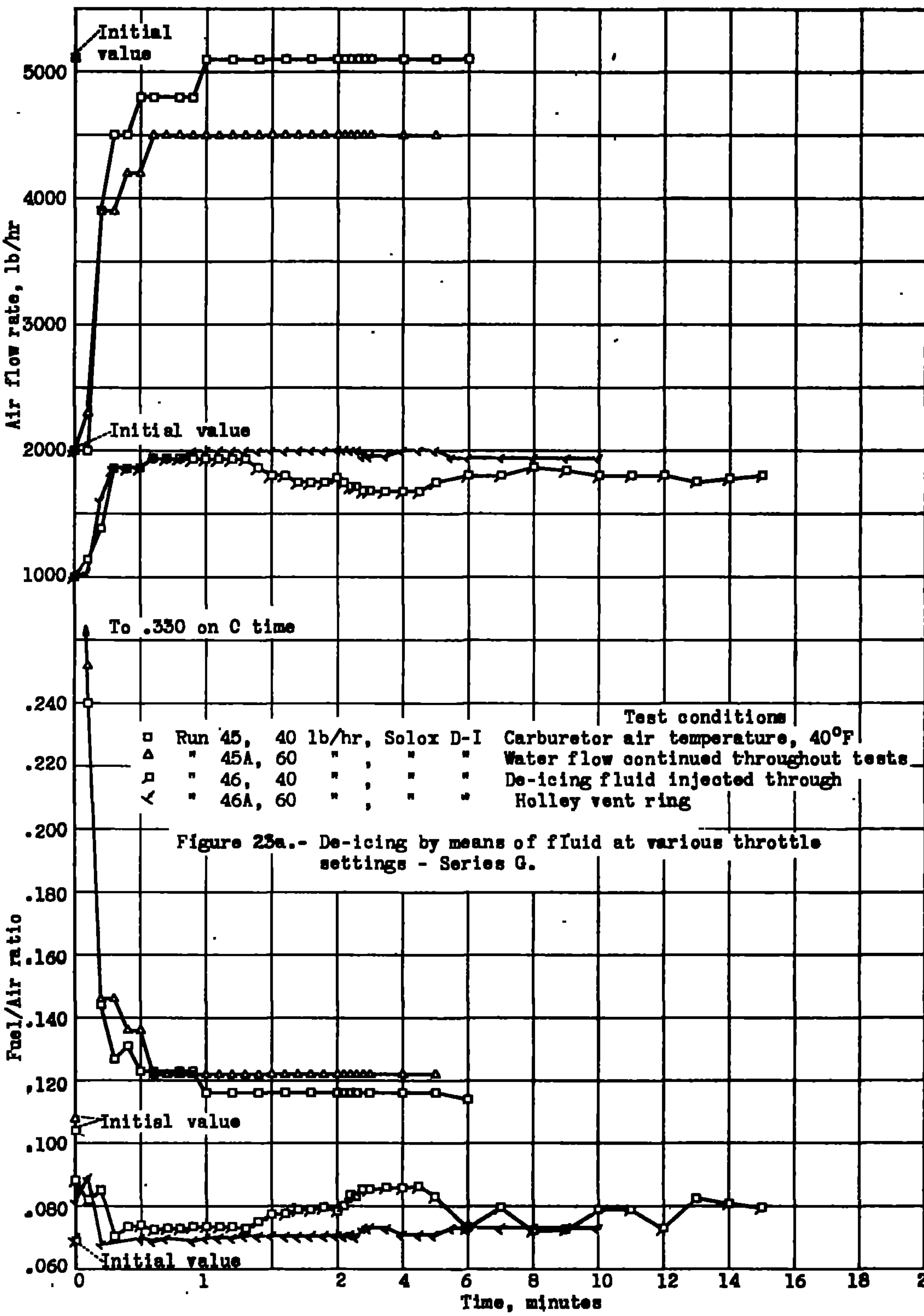


Figure 23a.- De-icing by means of fluid at various throttle settings - Series G.

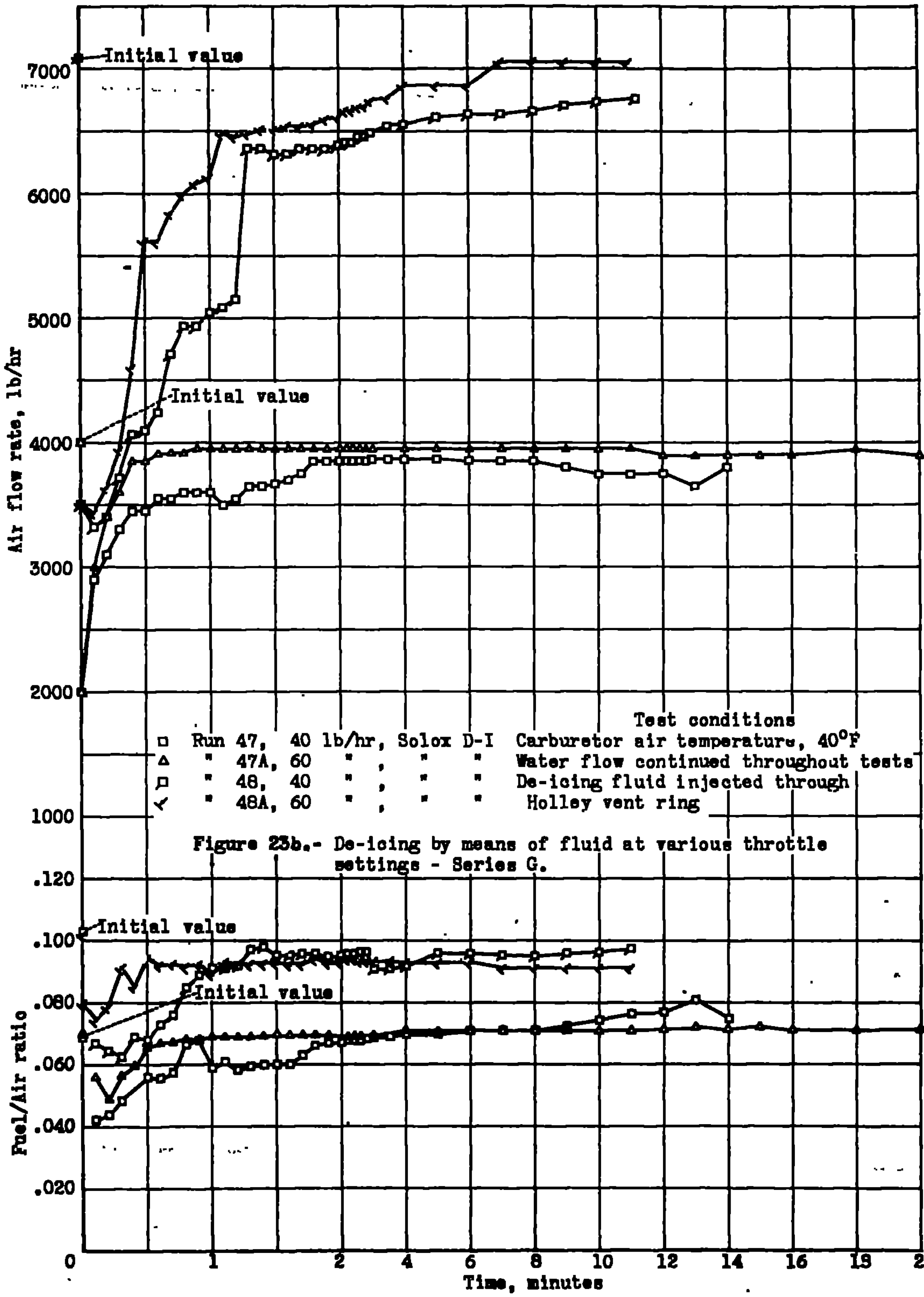


Figure 23b.- De-icing by means of fluid at various throttle settings - Series G.

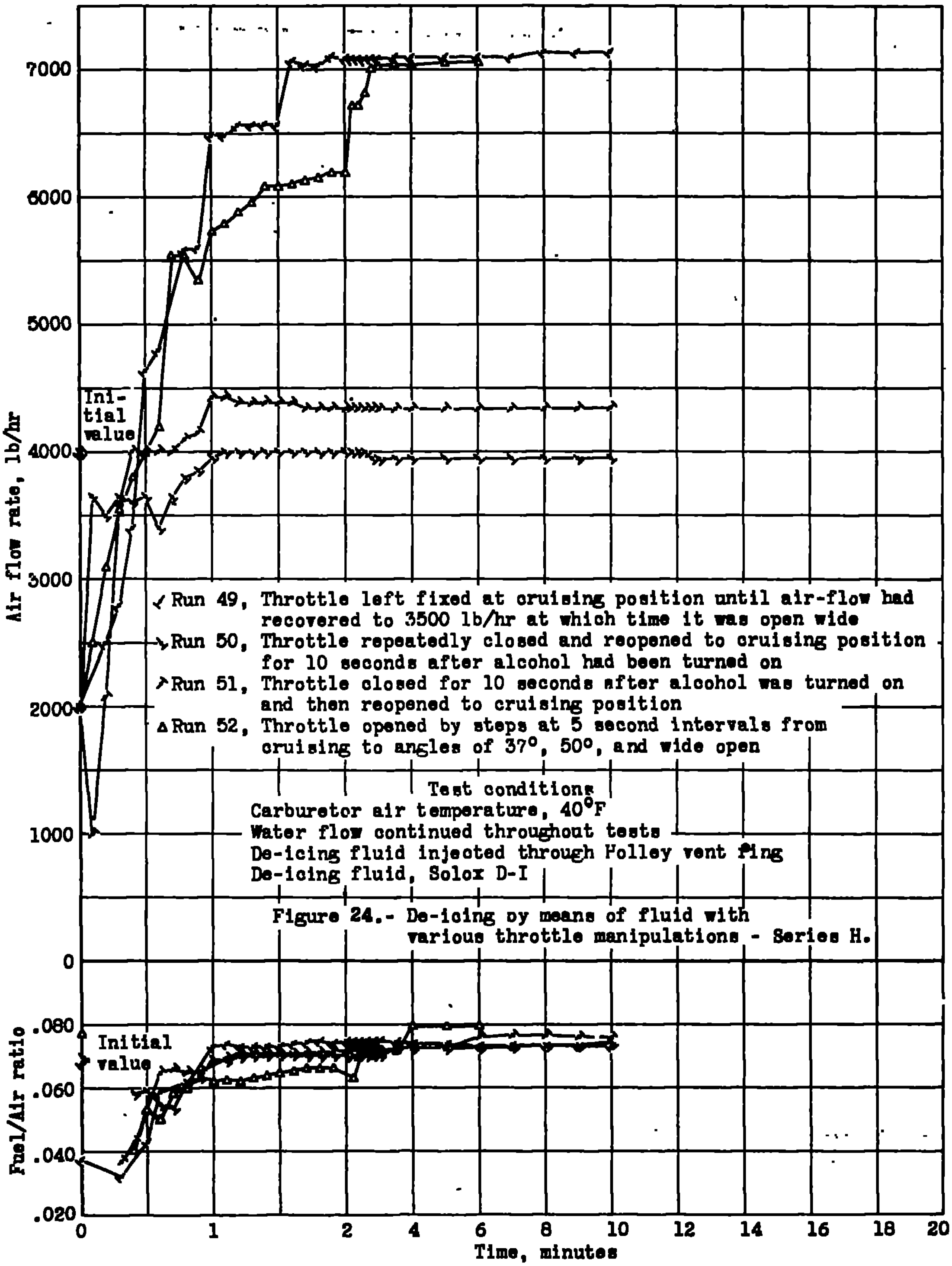


Figure 24.- De-icing by means of fluid with various throttle manipulations - Series H.

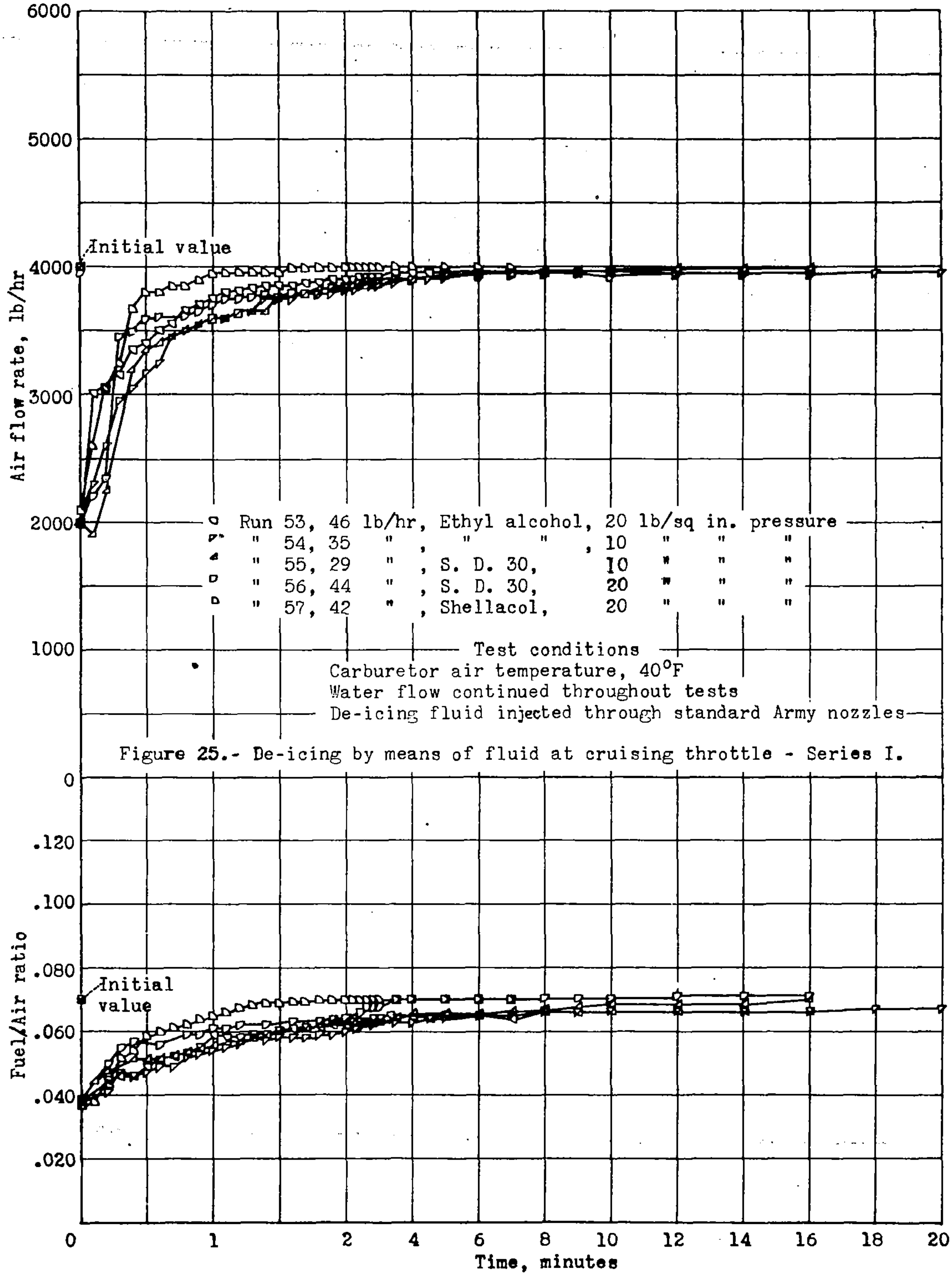


Figure 25.- De-icing by means of fluid at cruising throttle - Series I.

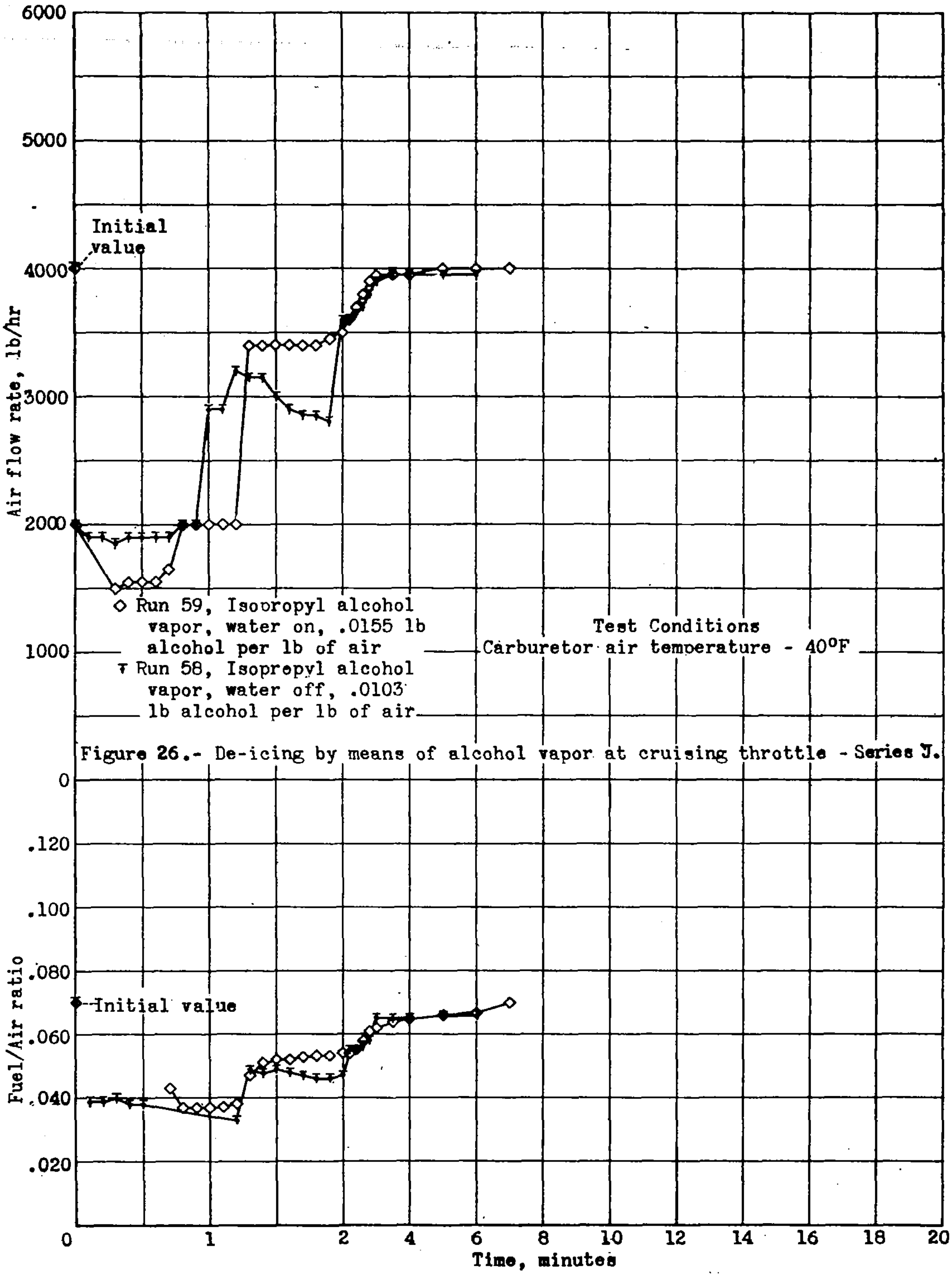


Figure 26.- De-icing by means of alcohol vapor at cruising throttle - Series J.

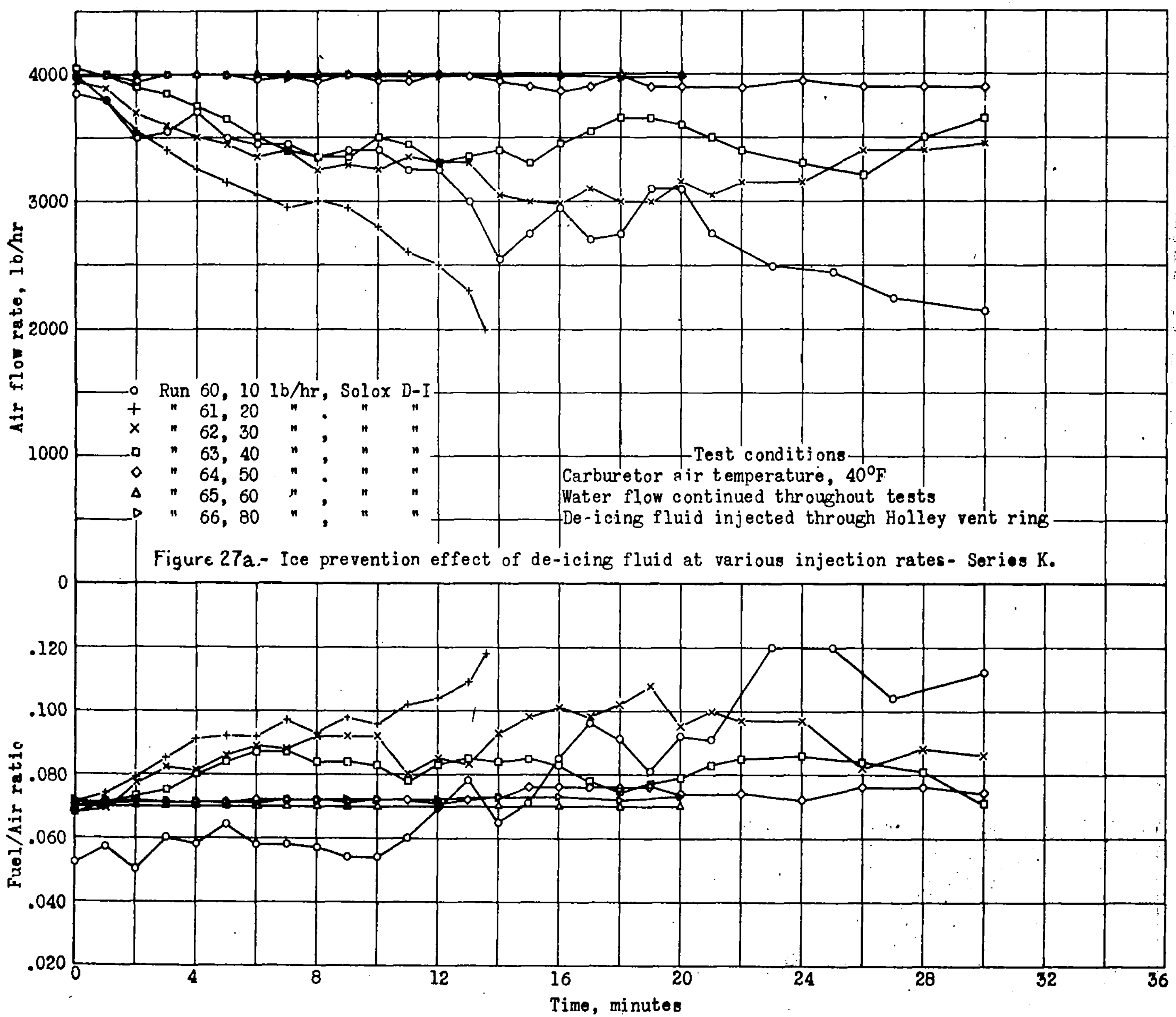


Figure 27a.- Ice prevention effect of de-icing fluid at various injection rates- Series K.

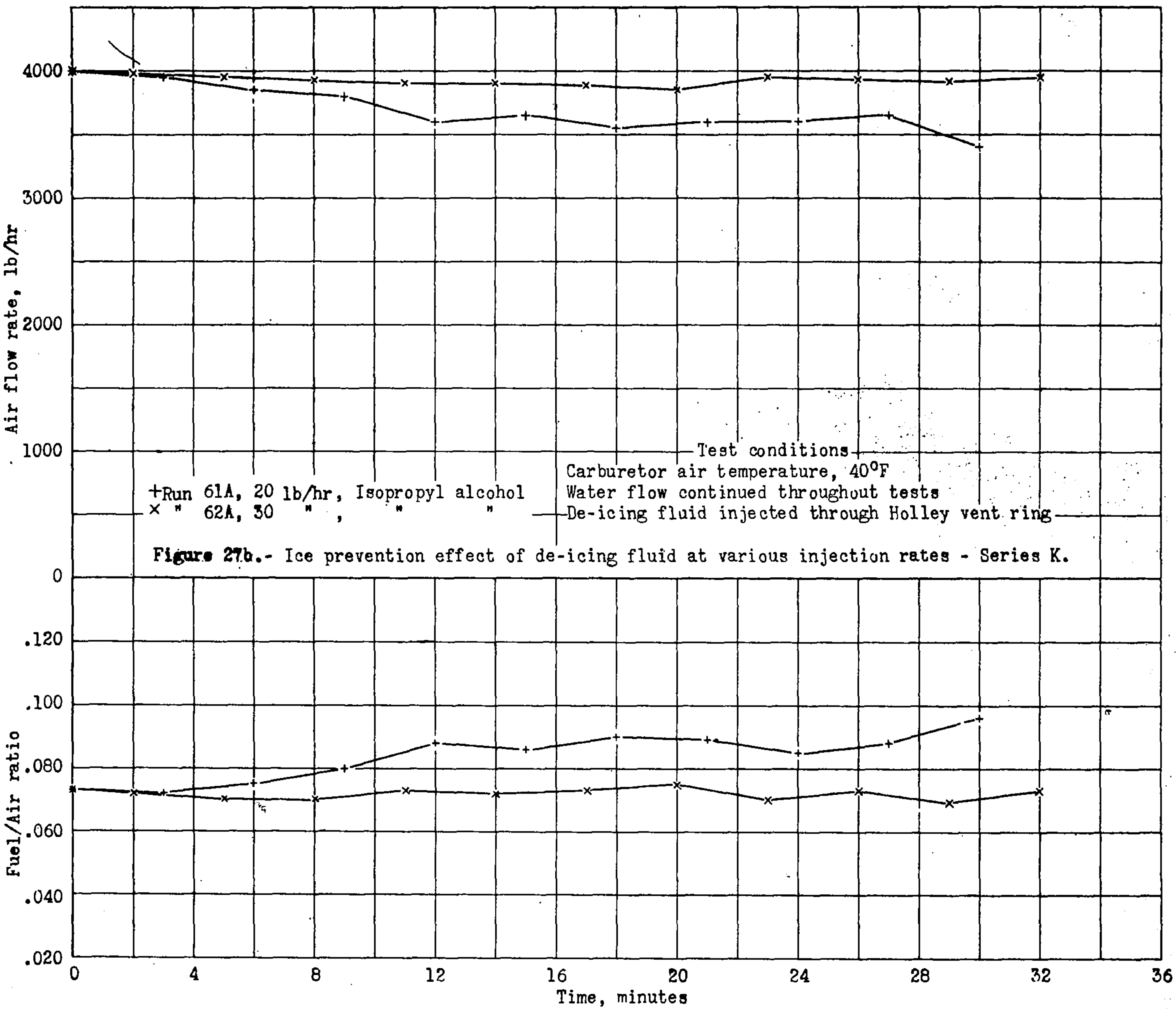


Figure 27b.- Ice prevention effect of de-icing fluid at various injection rates - Series K.

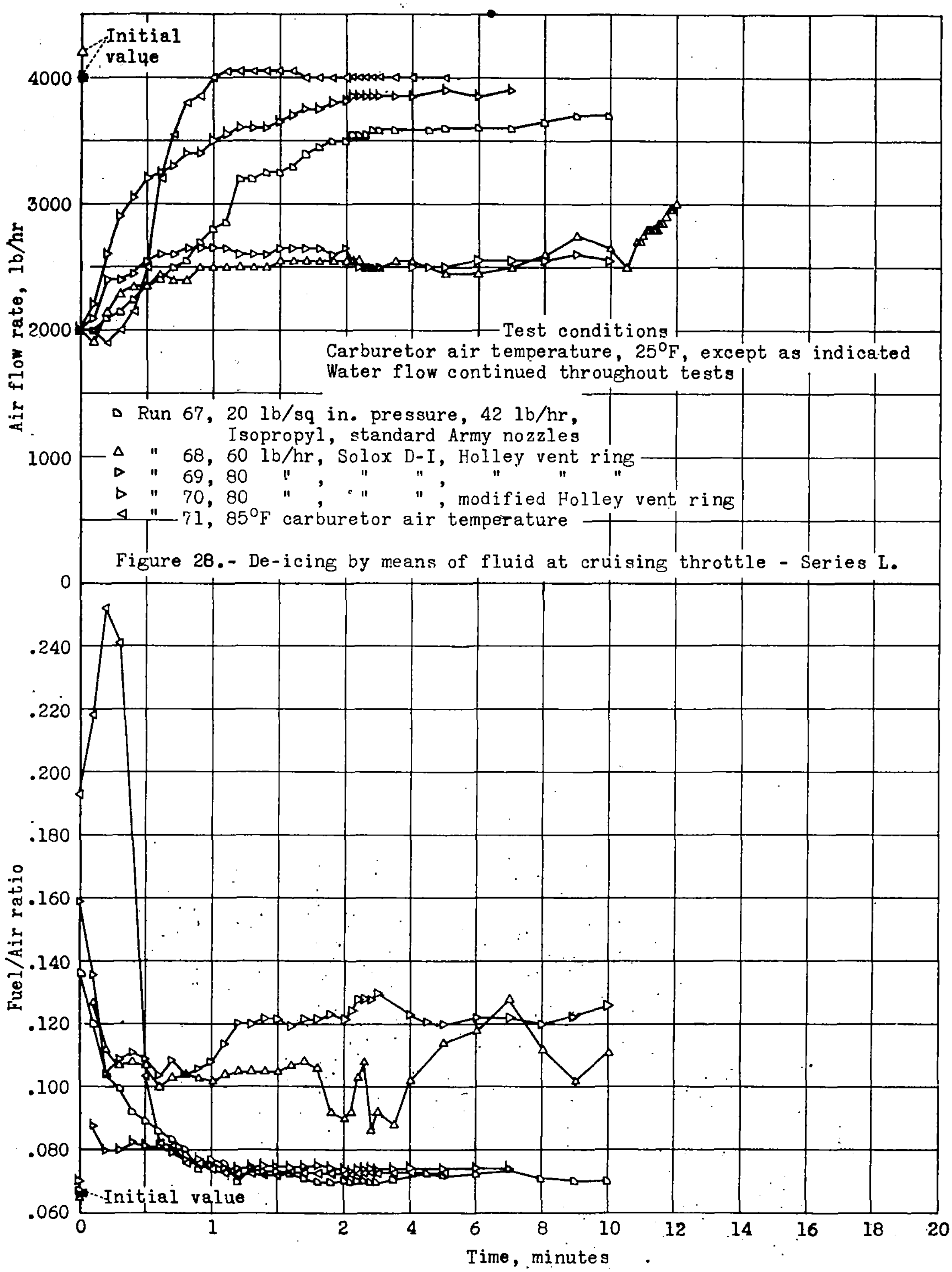


Figure 28.- De-icing by means of fluid at cruising throttle - Series L.

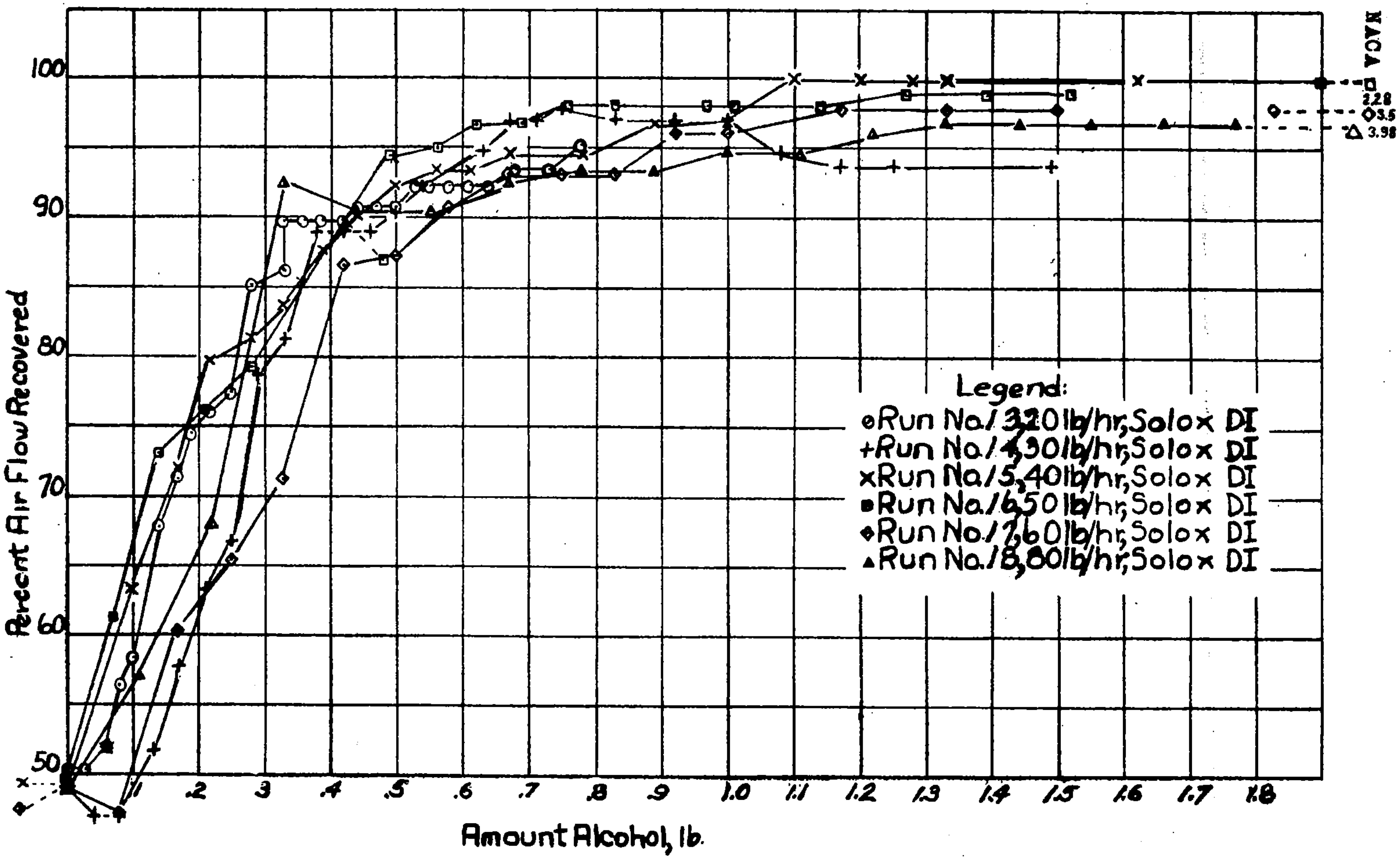


Figure 28. — Air Flow Recovery versus Alcohol Amount; Holley Ring; De-icing Fluid, Solox DI; Water Injected Throughout Tests, Initial Air Flow 4000 lb/hr, Initial Fuel Air Ratio .070 Series B

Fig. 29

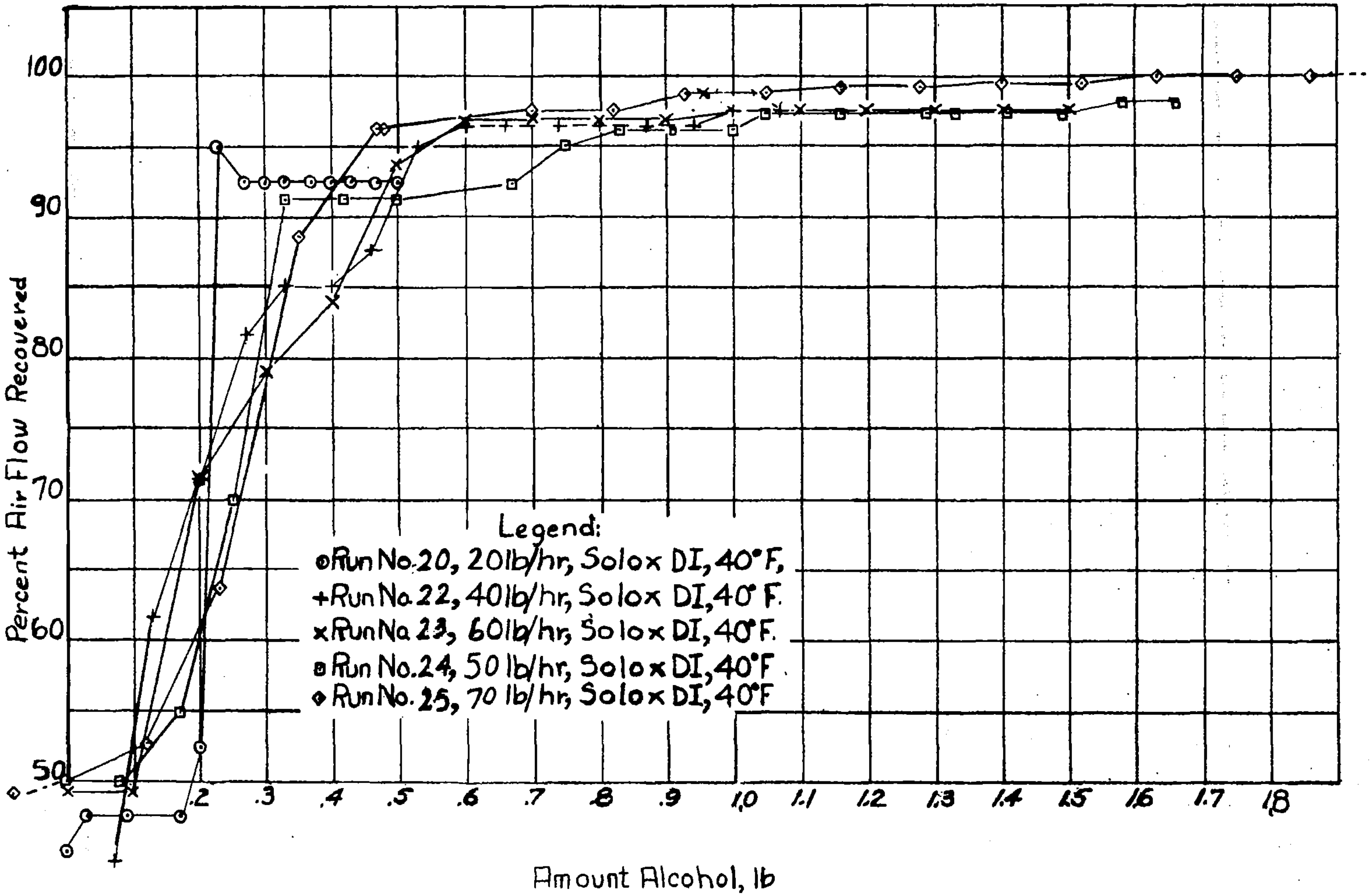


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Figure 30. — Air Flow Recovery versus Alcohol Amount; Holley Ring; De-icing Fluid, Solox DI; Water Discontinued When Alcohol Flow Started; Initial Air Flow 4000 lb/hr; Initial Fuel Air Ratio .070
Series C

Fig. 30

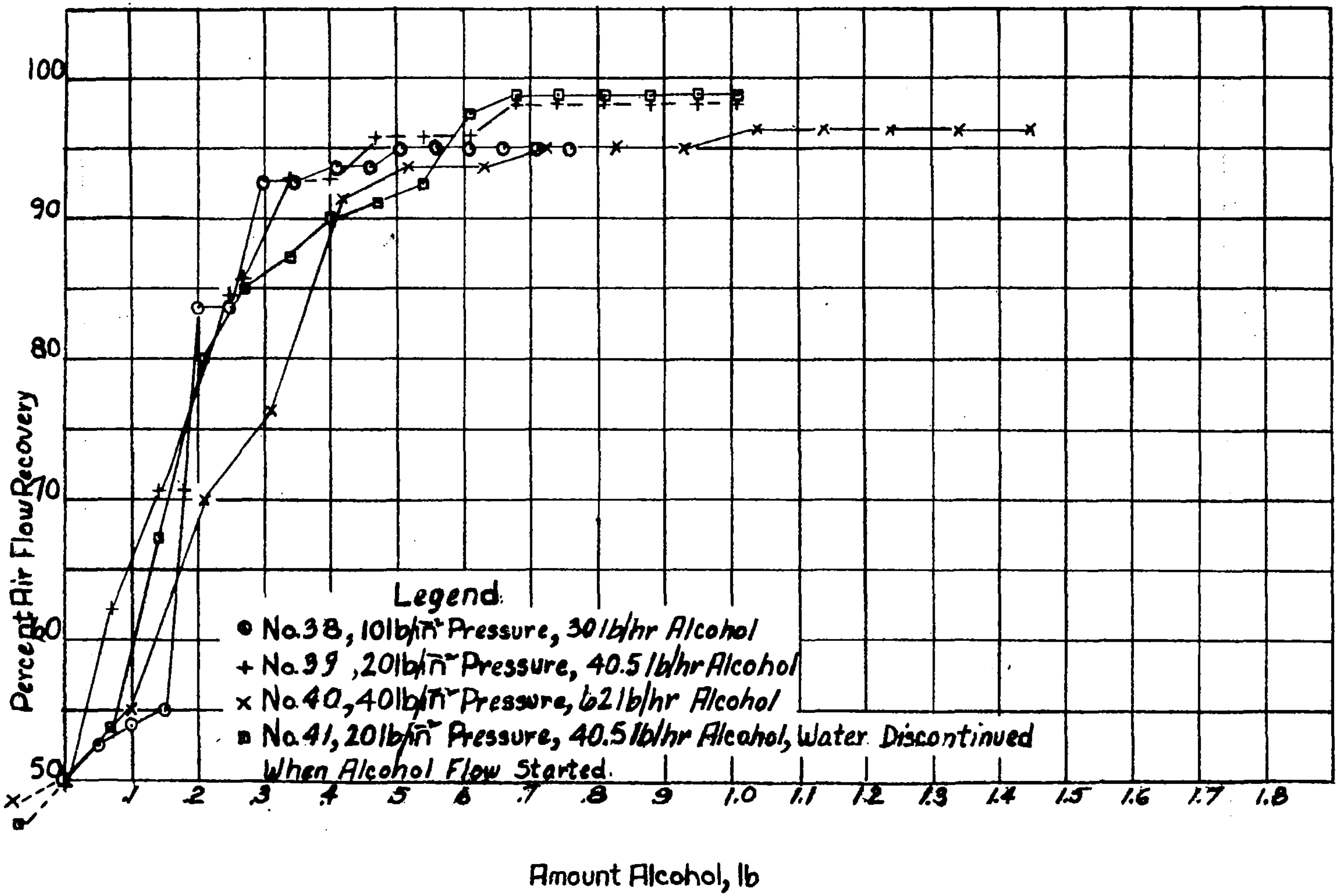

Figure 31. — Air Flow Recovery versus Alcohol Amount; Water Continued When Alcohol Flow Started; Four Standard Army Nozzles; De-icing Fluid, Isopropyl Alcohol; Initial Air Flow 4000 lb/hr; Initial Fuel Air Ratio .070; 40°F. Series E

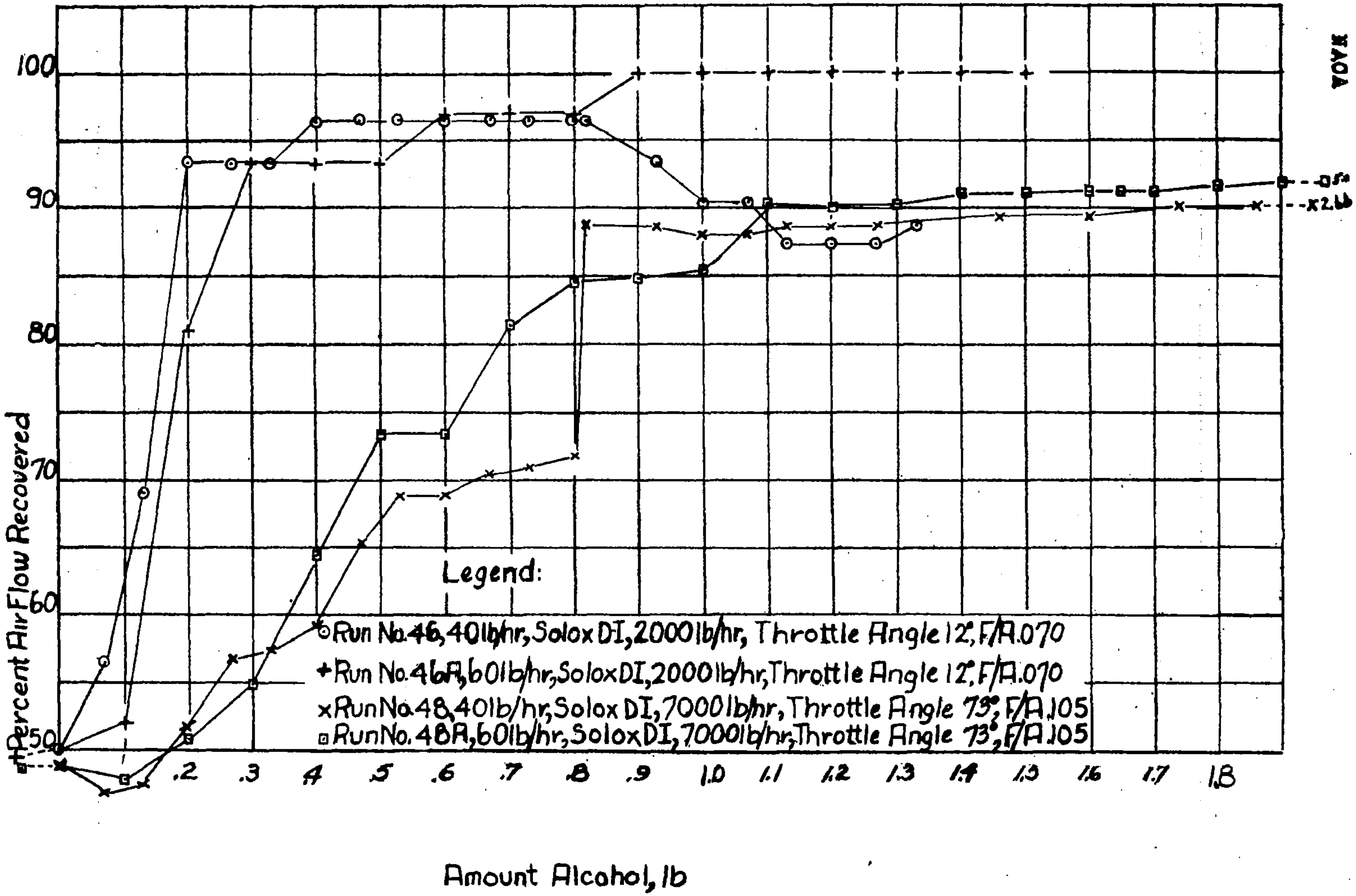

Figure 32. — Air Flow Recovery versus Alcohol Amount, Holley Ring; De-icing Fluid, Solox DI; Water Injected Throughout Tests,

Series G

NACA

FIG. 32

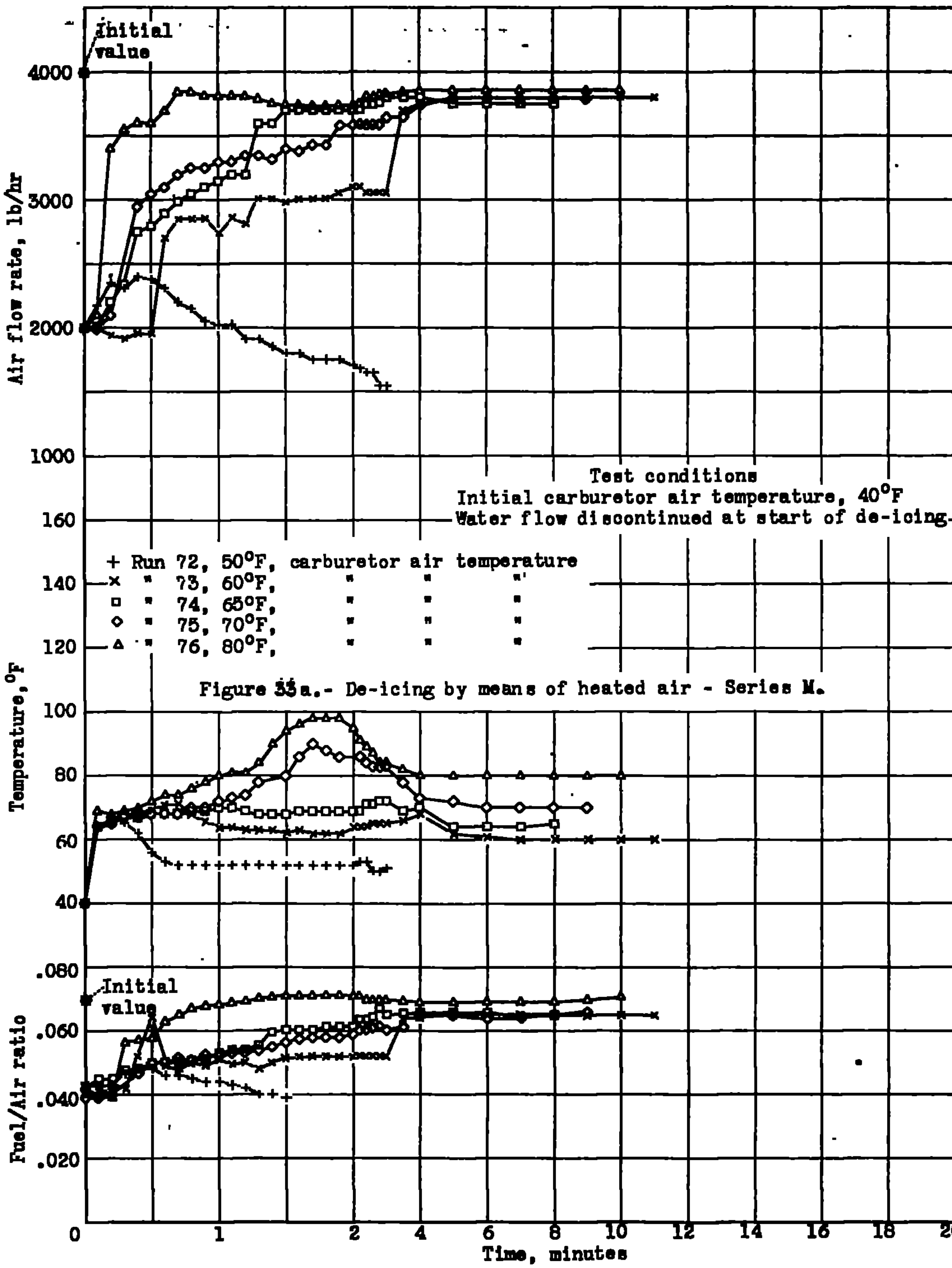

Figure 33a.- De-icing by means of heated air - Series M.

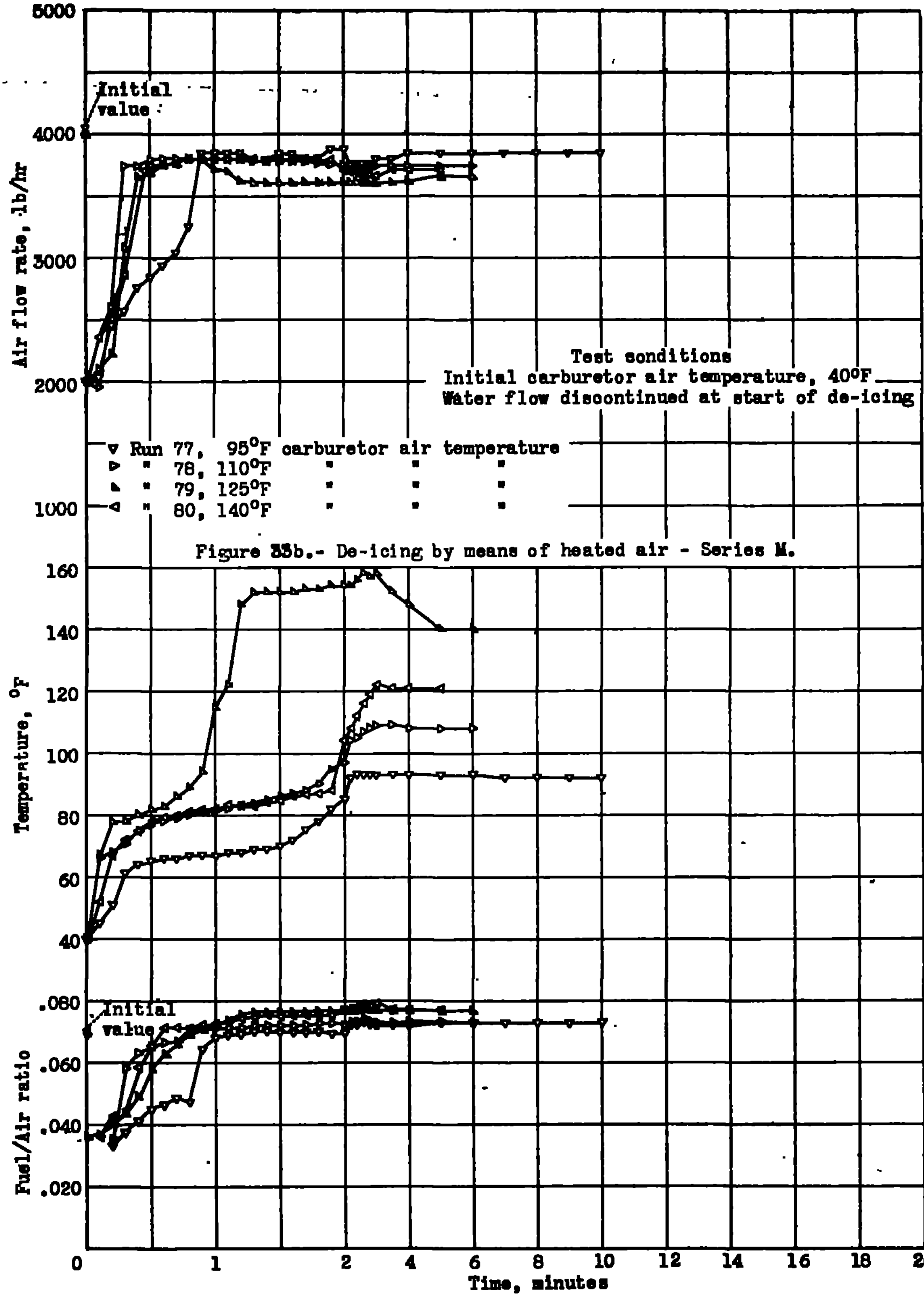

Figure 33b.- De-icing by means of heated air - Series M.

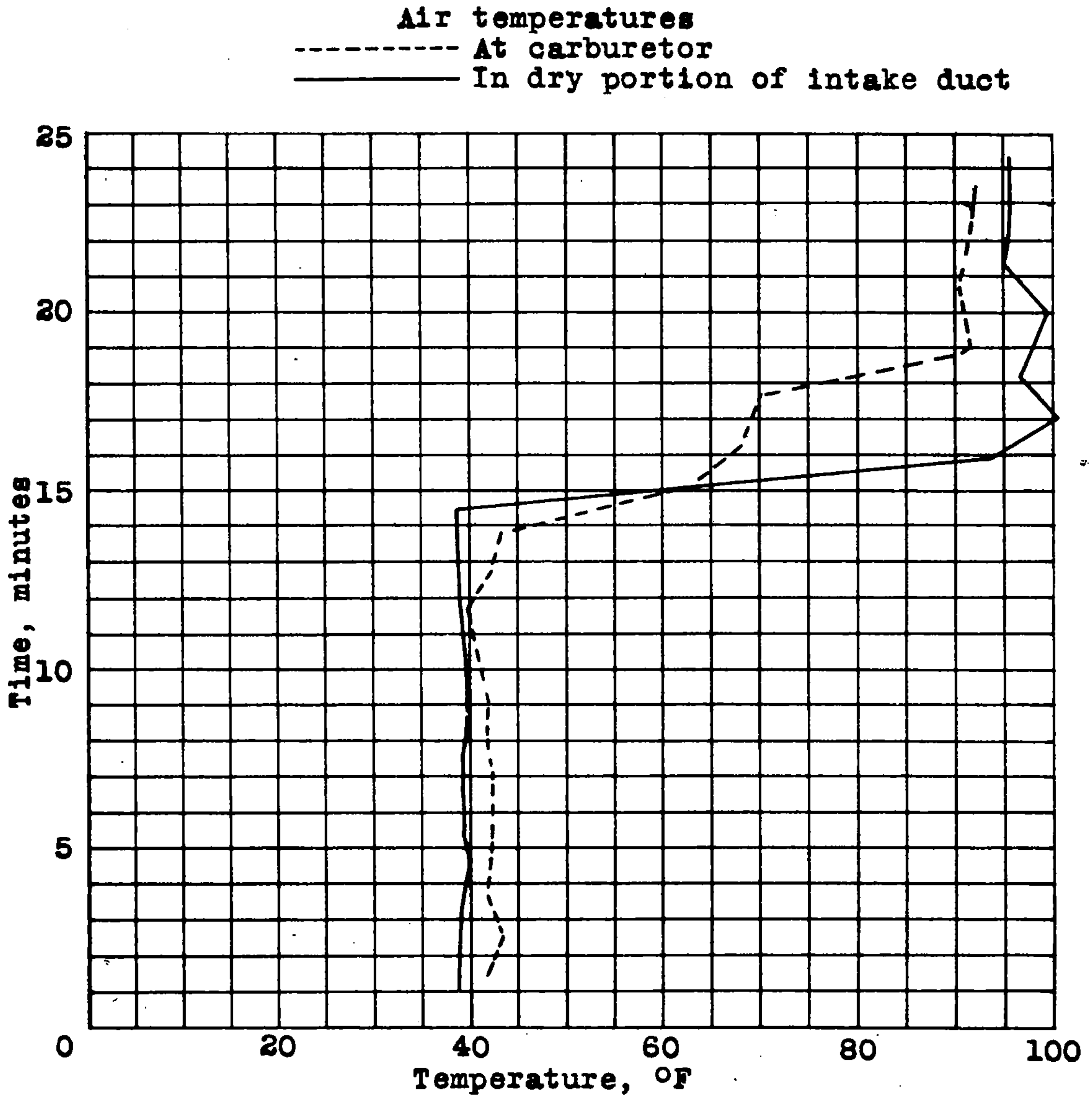

Figure 35.- History of carburetor air temperature and the air temperature in a dry portion of the intake duct during a heated air de-icing test, Run No. 77.